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**EXPERIMENTAL EVALUATION of VHF FM, SSB, and ACSSB in the
INTERFERENCE CONTEXT of the LAND MOBILE RADIO BANDS**

by

LUC BOUCHER, B. ENG.

A thesis submitted to the
Faculty of Graduate Studies and Research
in partial fulfillment of the requirements
for the degree of
Master of Engineering

Faculty of Engineering
Department of Systems and Computer Engineering
Carleton University

March, 1989

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ABSTRACT

Spectrum efficiency and system properties of analog VHF ACSSB, FM, and SSB in the interference context of the land mobile radio bands are defined and evaluated. An overview of the pilot-based SSB systems and their performance is presented. A comparison between the SSB, pilot SSB, and FM systems is carried out experimentally. The comparison involves parameters such as protection ratio, sensitivity, and interference criteria. Channel spacing, bandwidth, emitted spectrum, audio frequency response, factors influencing the reuse distance, and interference between and within the tested modulation schemes are also experimentally compared. Conventional objective and subjective evaluation methods and criteria are evaluated. An objective measurement method that produces results similar to the subjective disruptive measure is derived. Factors influencing the introduction of ACSSB, SSB or other new technologies in the land mobile bands are presented.

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Glossary of Symbols and Abbreviations

ACSB: Amplitude Compandored Single Sideband; usually referring to the Amplitude Companded pilot Single Sideband developed at Stanford University (Lusignan et al.).

ACSSB: Generally used to refer to the other Amplitude Companded Single Sideband systems, for example, the commercial ones.

AF: Audio Frequencies.

AFC: Automatic Frequency Control.

AGC: Automatic Gain Control.

ALC: Automatic Level Control.

AM: Amplitude Modulation.

CCIR: International Radio Consultative Committee.

CMOS: Complementary Metal-Oxide Semiconductor.

CNR: Carrier to Noise ratio.

CRC: The Communications Research Center of the Canadian Federal Government Department of Communications (DOC).

DOC: The Canadian Federal Government Department of Communications.

F_a: Assigned Frequency.

F_c: Carrier Frequency.

F_{sc}: Suppressed Carrier Frequency.

FM: Frequency Modulation.

FCC: The United States Federal Communications Commission.

FFSR: Feed Forward Signal Regeneration.

HF: The High Frequency band (3 to 30 MHz) of the Radio Frequency spectrum.

IF: Intermediate Frequency.

IM: Intermodulation products.

ITU: International Telecommunication Union.

J-N: Just Noticeable; refers to the just noticeable interference criteria.

J-N-N-M: Just Noticeable with no modulation; refers to the just noticeable interference criteria, taken when there is no modulation on the desired station.

kbps: Kilobits per second.

LPC: Linear Predictive Coding.

MOS: Metal-Oxide Semiconductor.

NBFM: Narrowband Frequency Modulation.

PEP: Peak Envelope Power.

PTT: The Push to Talk button of the microphone of a transceiver.

RF: Radio Frequencies.

RSS: Radio Standard Specifications. Refers to Standard emitted by the DOC Telecommunication regulatory Service.

RX: Receiver.

SINAD: Is the acronym for Signal plus Noise And Distortion.

SMS: The Spectrum Management Section of DOC.

SNR: Signal to Noise Ratio.

SSB: Single Sideband Modulation.

TAB: Tone Above Band.

TCXO: Temperature Compensated Crystal Oscillator.

TIB: Tone In Band.

TTIB: Transparent Tone In Band.

TX: Transmitter.

UHF: The Ultra High Frequency band of the Radio Frequency spectrum (300 to 3000 MHz).

VHF: The Very High Frequency band of the Radio Frequency spectrum (30 to 300 MHz).

CHAPTER 1

INTRODUCTION

1.1 BACKGROUND

The demand for commercial land mobile radio services has increased to the point where existing spectrum allocation in the VHF and UHF bands has become nearly saturated in major Canadian urban centers.

Further growth in the use of civil land mobile radio will depend critically on using the radio frequency spectrum more efficiently, particularly in the VHF and UHF bands. Many techniques can be employed to improve the spectrum utilization, such as: dynamic channel assignments or "trunking", digital techniques, diversity techniques in reception and transmission,¹ and cellular schemes.

Not least significant, however, is to replace the Frequency Modulation (FM) or Amplitude Modulation (AM) schemes by one which utilizes the spectrum more efficiently. Neither dynamic channel assignment nor cellular schemes are tied to any particular modulation system and would work equally well with narrowband systems such as Single Sideband (SSB) as with wideband systems such as FM [1]. In view of this narrowband advantage, it is reasonable to ask why SSB was not adopted previously in the civil land mobile radio services.

SSB has effectively been considered in the past for land mobile radios. In the late 1950's, for example, it was considered for domestic use at VHF frequencies [2-4]. There were, however, several problems associated with its usage. Frequency stability and rapid fading of the signal at VHF were major problems. Some of the techniques such as the use of a pilot tone for Automatic Frequency Control (AFC), variable pilot power ("pumping")

¹ Although diversity techniques in transmission might not at first appear to save spectrum, having two low power base stations geographically separated instead of one high power one could be an example of more efficient usage.

to reduce the intermodulation products (IM) of the linear power amplifier, the use of pre-emphasis and amplitude compression to improve the voice quality and reduce the peak to average ratio, etc.,— that are now being used to solve these problems were known at the time (see for example the 1956 special IRE (now IEEE) issue on SSB [4], or the 1964 book on SSB [5]), but more circuit stages than for AM or FM equipment were needed to solve these problems and to modulate and demodulate the SSB signal. That extra circuitry made SSB equipment more costly and more bulky, and at that time, the simplicity of the radio systems was considered more important than the efficient use of the spectrum. Also, without these techniques, subjective evaluation of SSB performance compared to FM indicated that SSB was less attractive for land mobile usage at these frequencies, and accordingly, FM systems were given preference: FM had the advantage of economical implementation and good voice quality, although this latter quality was only achieved at the expense of a wider bandwidth.

Subsequently, the interest for SSB usage in the VHF and UHF land mobile bands was minimal. Recently, however, the situation has changed. A number of studies have demonstrated that these and other processing techniques could be economically implemented with today's high level of circuit integration, to yield SSB systems with performance similar to that of FM. These systems are generally referred to as pilot-based SSB systems.

For example, in 1978, a study supported by the UHF Task Force of the U.S. Federal Communications Commission (FCC) suggested that the use of suppressed carrier pilot SSB, along with amplitude and frequency companding could yield from 7 to 10 times more channels in the existing mobile radio bands [6–18].

In addition, other research conducted in the U.S. [19] and in many other countries, such as in the U.K. [1] [20–43], Canada [44–49], and Japan [50–55], have investigated SSB for VHF and UHF land mobile use, and SSB is used in VHF land mobile applications in Yugoslavia [56]. Pilot SSB has also been developed for satellite applications [57–66].

As a result of the U.S. research, VHF Amplitude Companded Single Sideband (AC-SSB) commercial units have appeared on the market (basically, ACSSB is similar to SSB, except that a pilot tone and some baseband processing such as amplitude companding and pre-emphasis are added to it). However, the possible spectral advantage of ACSSB compared to FM has since been the subject of a major controversy (see for example [67–69]).

Although only a few studies were undertaken to experimentally evaluate this new technology and to compare its performance with the existing FM systems, its possible use in the VHF band has been the subject of much comments from various parties. Supporters claim that ACSSB systems can be allocated a 5 kHz channel spacing, and can be interleaved within the presently allocated 25 and 30 kHz land mobile channels. Critics claim that pilot SSB is not suited for land mobile operations and is not as good as actual FM systems.²

Part of this problem is related to the definition of spectrum efficiency, in the land mobile bands, and to the lack of unified criteria to evaluate its parameters.

Calculations of spectrum efficiency for different radio systems have often been made strictly based on the spectrum occupied by a channel, i.e., on the basis of the maximum number of channels that can be assigned in a given frequency band. This is a valid criterion in an interference-free environment, but in the land mobile radio service, an equivalently important parameter is the number of people in an extended area that can use a given amount of spectrum. In this measure (users per unit area per Hz), the separation distance required to re-use the same channel is as important as the actual spectrum occupied by a channel. This separation distance depends somewhat (but not exclusively, as will be shown in this study) on the acceptable desired to undesired protection ratio for co-channel interference; the smaller the ratio, the closer the co-channel separation distance will be. The calculation of spectrum efficiency therefore rests on the correct evaluation of the respective channel bandwidth of the various systems, as well as on the correct estimation of their re-use distance.

Unfortunately, no standard evaluation method exists to determine the protection ratios or the re-use distance, and no standard interference criteria has been defined for the evaluation of the protection ratios. Moreover, there is no unified method of establishing the channel spacing of new technologies.

² Many groups have studied the proposal advocated by the authors of the FCC's UHF Task Force report [8] suggesting the substitution of FM for pilot SSB systems in the land mobile radio services. Their comments have been reported in the "Comments to the Notice of Inquiry" (FCC PR Docket 82-10, June 1982), and in the comments to the "Interim Report" that preceded the Final Report entitled: "Future Private Land Mobile Telecommunications requirements" [70]. These comments are summarized in the Appendix I and II of that final report. An ad hoc committee of the Electrical Industries Association (EIA) has also strongly contested the use of pilot SSB in VHF as a practical solution [71].

As a result, the data comparing the ACSSB and the FM efficiency differs from one study to another. In a recent paper by a member of the U.S. National Telecommunications and Information Administration [72], some of the few available set of protection ratios on ACSSB and FM were gathered, in order to calculate the spectrum efficiencies of these two systems. It was found that:

"5 kHz ACSSB systems appear to be about 1.5 to 8.4 times more efficient than 25 kHz FM systems. The large variation arises mainly from the differences in measurements techniques and criteria which tends to hide the real difference between the two systems. This argues for the need to have standard measurement techniques and criteria in future spectrum efficiency measurements".

In the discussion of the various protection ratio measurements it is concluded that:

"Because the methods of measurement, the measurement criteria, and the measuring signals, were very different, and because of possible differences between the tested equipments of the same nominal type, the protection ratio measurements, as a whole, are incommensurable".

Hence, it is not surprising that, in their conclusions of the final report *"Future Private Land Mobile Telecommunications Requirements"* [70], the FCC Planning Staff reported that:

"Before the FCC can provide any permanent channels for SSB narrowband systems within present allocations, a determination of the interference levels within and between the pilot SSB and FM systems, the required separation distances, and the actual transmitted bandwidth of pilot SSB must be obtained.... these and many other compatibility questions must be resolved prior to implementation of any new allocation scheme".

1.2 OBJECTIVES

Presently, engineers trying to compare the analog FM, ACSSB, and SSB systems are faced with a very limited number of studies of very limited scope. For example, the FCC study [73] contains some protection ratios of ACSSB into ACSSB, ACSSB into FM, and FM into ACSSB, but practically no comparative measure on FM into FM. Moreover, comparative protection ratios for SSB could not be found in any of the studies. Also, using the results of the few available studies, the comparison of the spectral efficiency of FM and ACSSB is not conclusive because of the incompatibilities between the results of the different studies.

Consequently, the major goal of this study is to determine, through experimental evaluation, the important parameters to consider in a spectral efficiency comparison of the analog modulation schemes used in the land mobile bands, and to compare and evaluate the testing methods, the measurement techniques, and the criteria that are generally utilized to determine these parameters in performance evaluations of FM, ACSSB and SSB systems. Based on the results obtained, the channel spacing that should be allocated to ACSSB, SSB, and to new technologies introduced in the VHF band will be determined, re use distance of the various schemes will be compared, and their spectrum efficiency evaluated. The most suitable evaluation techniques and criteria for the land mobile bands will be suggested as possible unified method for future measurements.

1.3 ORGANIZATION

Before getting into the experimental measurements part of this study, the evaluation methods and criteria used have to be clearly defined. This is the subject of chapter 2. Spectrum efficiency, sensitivity measures, and interference criteria are discussed and defined. Spectrum efficiency calculations as applied to the land mobile environment are reviewed. The sensitivity measures presently used for FM, SSB and ACSSB are examined, and one method is chosen to be used with the 3 different systems under test. The interference context of the land mobile environment is also reviewed. The protection ratio measurement techniques as well as the various subjective and objective interference criteria are described, and the interpretation of the protection ratio is discussed. The mobile radio communication model and the propagation loss equation that will be used for the interfering distance calculations are described.

Chapter 3 contains the results of the experimental evaluation of three FM, one ACSSB, and one SSB system.

Their utilized bandwidth is evaluated by measures of the emitted spectrum under various modulation conditions. The differences in the emissions are examined in order to establish tentative channel spacing values for the SSB and ACSSB systems. The receiver's sensitivity of each system is measured. The experimental test set-up and the calibration procedure is described, and a number of subjective and objective protection ratio measures is obtained for each system. Data is obtained and compared for interference between identical modulation schemes as well as for combinations of the three schemes under test. The factors influencing the re-use distance are determined, and the various interference criteria are judged for their appropriateness to be used in a comparison of the performances of the various systems.

From the collected data, an objective measurement method that produces results similar to the subjective disruptive measure is derived and consideration is given to a simplified automated evaluation method.

In the last sections of chapter 3, the harmful effect of the adjacent channels spurious emissions on the dynamic range of a receiver is examined, the audio frequency response of the tested systems are compared, and, using the results of this study, the spectrum efficiencies of ACSSB, FM, and SSB are evaluated and compared.

In the conclusion, a summary of this study and of its findings is presented, possible solutions to identified problems are described, the impact of ACSSB in the land mobile bands is discussed, and a description of further work is given. Some of the conclusions derived for the tested systems are generalized and extended to the introduction, in the land mobile band, of other new technologies.

A review of the problems associated with the conventional usage of SSB in the land mobile bands, and a summary of the recent pilot-based SSB research involved in finding a solution to these problems is presented in Appendix D.

CHAPTER 2

EVALUATION METHODS and INTERFERENCE CRITERIA

2.1 CALCULATION OF SPECTRUM EFFICIENCY

Spectrum efficiency can generally be defined as a measure of the number of users per unit (land) area per Hz that can use the service with a given quality of communication. It can be calculated in many ways, using various parameters (e.g., [67-69] [108-111]). For this study, calculations will be simplified, based on a number of assumptions. For example, trunking (dynamic channel assignment) certainly has an important effect on the calculations of the number of users serviced using a given amount of spectrum, and by its implementation, the spectrum efficiency is increased. But in this study, knowing that trunking will increase the spectrum efficiency by a factor of "x", will not be useful in the comparison of the tested modulation schemes, since this improvement will apply as well for one scheme as for the other. Hence, parameters such as traffic volume and blocking probability for a connection, for example, can be omitted.

In order to define the spectrum efficiency parameters that are important for this study, the land mobile environment will be characterized by a model. The model is based on the assumption that several fixed stations are geographically scattered over a given area (figure 2.1-A) in a manner that combines minimum overlap of the individual service areas, with full coverage of the overall service area. It is well known that optimal theoretical coverage is given by a honeycomb structure, which is the closest practical approach to a regular pattern of circular service areas (figure 2.1-B). Each mobile station is assumed to communicate via the fixed station of the cell in which it happens to be. Because a transmitter's range of action ends at a certain distance, the use of a given assigned frequency by this transmitter does not prohibit the use of that same frequency beyond that distance. This geographical re-use of channel frequencies is one of the principal factors governing spectrum utilization, because it enables a certain pattern, in which each frequency is used once, to be repeated ad

infinitum. In this way, each pattern repetition permits another number of network users to be serviced, without having to increase the total bandwidth available.

In this model, it is assumed that the radio receivers have enough selectivity and linearity that they do not suffer interference from the communications carried on at the other frequencies. This assumption is based on the fact that the receivers should have a high resistance to interference from adjacent channels, and that this resistance should increase with the frequency separation. In the honeycomb model, the risk of interference is in fact presented only by communications taking place at the same frequency, notable in six cells roughly situated in a circle at intervals of 60° (figure 2.1-C). The severity of this co-channel interference determines how many cells will have to be interposed, and this in turn will decide how many channels (or channel groups) will be required. In figure 2.1-B, this number is 9 (note that f_x can represent a single channel as well as a group of channels).

In figure 2.1-C, one sees that the area of interference between two base stations has a radius of d_A , which represents the required separation distance between the fixed stations. This separation is usually referred to as the re-use distance. The mobile, because of various limitations (e.g., transmitted power, antenna height, etc.) can operate within a much smaller area, of radius d_c , which represents the coverage area within which the base station can receive its signal, with a given quality, in the presence of the interference from the other fixed stations.

Given that a comparison is done on different modulation systems that have identical parameters for their fixed stations (i.e., identical rated power, antenna gains, antenna heights, operating frequencies, etc.), and identical parameters for their mobile stations, and that an identical signal degradation criteria is used for all the different systems, only two parameters remain critical to effectively compare the spectrum efficiencies of the different systems: the interfering (re-use) distance and the frequency separation (channel spacing) between the fixed stations.

The interfering distance becomes a parameter since it relates directly to the number of users per unit area, at a given grade of service quality. The channel spacing relates to the number of users per unit spectrum (per Hz). If, for example, system A requires a separation distance of 100 miles between its base stations; it has therefore an interference area of πd_A^2

31416 square miles, or a density of $1/\text{area} = 31.83 \times 10^{-6}$ base station per square mile. If system B, under identical conditions, requires separation distances of 50 miles, then the

interference area is 7854 square miles and the density, 127.32×10^{-6} base station per square mile. The ratio of the density of system B to system A is 4, showing that 4 base stations of the system B type could be put into the area occupied by one of the A type. Consequently, B is 4 times more spectrally efficient than A since, under identical conditions, 4 times more base stations can be provided by B than A. Moreover, if system A requires 30 kHz channel spacing, and system B requires, under similar condition, 10 kHz channel spacing, a factor of 3 in the number of users per Hz (and in the spectrum efficiency) is obtained for system B compared to system A. That is, 3 times more channels of system B can be used to replace system A, and still provide the same quality of service. Overall, in this example, 4 times more base stations and 3 times more channels can be provided by system B. Thus, if one were to replace all systems A with systems B, $4 \times 3 = 12$ times more stations could be put in the area of 100 miles radius used by system A. In other words, system B is 12 times more efficient than system A.

In this study, the evaluation of the two above parameters, needed to compare the spectrum efficiency of different modulation systems in the land mobile environment, will be done essentially using similar testing conditions and criteria for the various tested systems.

A : General model of mobile radio network. FS = fixed station with service area; mobiles (X) are scattered in the region, some are within a service area, others are not, whilst some are in two overlapping areas.

B : Mobile radio network with minimum overlapping areas. $f_1 - f_6$: frequency channels (or groups) used by base stations.

C : Definition of distances, used in the interference calculations.

FIGURE 2.1 : MOBILE RADIO MODEL
(from ref. 108)

2.2 SENSITIVITY EVALUATION METHODS

Because of the differences in the properties of FM, ACSSB, and SSB, different sensitivity evaluation methods have been used in the past to evaluate these systems. The sensitivity for FM is practically always given using the 12 dB SINAD. For SSB, the 12 dB SINAD is also often utilized, but ACSSB has generally been evaluated using the 20 dB quieting method (see for example the manufacturer specifications in appendix A). The difficulty that arises when the SINAD is used for ACSSB relates to the fact that the measure in this case requires two tones: one for the modulated RF pilot, and one for the modulated RF 1 kHz tone. The power level at which these signals should be set has been the subject of some controversy, and various values of 12 dB SINAD have been obtained for similar units.

Generally, to measure receiver sensitivity, three major methods are available [112]: the quieting method, the SINAD method or the noise figure method. The latter method is most often used when designing new equipment, and is difficult to measure when making production tests. Accordingly, because of their easier measurement method, only the two former methods will be considered here.

2.2.1 Quieting Characteristic

The output signal of a receiver consists of random noise when no signal is applied to the antenna terminal. This noise is band-limited by the audio response of the receiver, and in the case of superheterodyne receivers, is band-limited by the intermediate frequency (IF) selectivity. The noise power comes from the amplified thermal (Johnson) noise of the receiver input terminal source resistance (the resistance that the receiver input "sees") and from the noise sources within the receiver itself. When the receiver is connected to an antenna, additional input noise is introduced from galactic, atmospheric, and man made sources.

When an unmodulated signal is applied to the receiver, the noise output generally decreases. In most AM receivers, this is due to a reduction in gain as the automatic gain control (AGC) circuit acts to hold the detector signal level constant for variations in the received signal level. In FM receivers, the noise output drops as the input signal captures the limiting stages in the receiver. This property of a receiver in the presence of an unmodulated input signal is termed the quieting characteristic.

In the quieting method, an unmodulated RF signal (referred to as a single RF tone) applied to the antenna input of a receiver produces a specified amount of noise power reduction at the audio output. The method provides a measure of the minimum RF level that eliminates, by limiting action, the bulk of the noise in the receiver audio output.

Quieting sensitivity is usually stated as the single RF tone input necessary for either 10, 20 or 30 dB quieting. However, receivers with the same IF bandpass, but with different audio roll-off characteristics, produce a different quieting value. This inability of the quieting method to distinguish between IF and audio response limits its usefulness. Only receivers of identical design can be compared. The method's main advantage centers on its simplicity and on the fact that only one RF signal generator need to be used.

2.2.2 SINAD

This type of sensitivity test can be used with any voice communication equipment since it gives a measure that is indicative of the expected intelligibility for a given signal strength. SINAD is an acronym of "signal plus noise and distortion".

SINAD is expressed mathematically by a value in decibel, given by:

$$\text{SINAD} = 20 \log_{10} \left[\frac{(\text{Signal} + \text{noise} + \text{distortion})}{(\text{Noise} + \text{Distortion})} \right],$$

where the parameters are expressed by their RMS voltage values. The general method of measurement is described in section 3.2. Commercial test instruments called SINAD meter or audio distortion analysers can be used for this measure.

As examples of what typical SINAD values represent, a system with a SINAD of 40 dB would have only one percent (measured as a voltage) of noise and distortion present at the output. A SINAD of 20 dB would represent 10 percent of noise and distortion. The figure traditionally used for measuring FM receiver sensitivity is 12 dB, which represents 25 percent noise and distortion. The value of 12 dB SINAD for FM is customary for several good reasons. One is the fact that, for FM, a 12 dB SINAD signal is close to the minimum required for good speech intelligibility [113]. Another is that this value is relatively close to the knee of the Signal to Noise Ratio (SNR) versus Carrier to Noise Ratio (CNR) FM improvement curve: as the RF signal level is decreased below the 12 dB SINAD, the SINAD value decreases rapidly.

It will be shown in chapter 3 that the 12 dB SINAD level is also close to the minimum required for good speech intelligibility for the ACSSB and SSB systems. A value of 6 dB SINAD will be shown as being the value at which disturbing degradation of the transmitted message (disruptive level; the modulating signal is masked by the noise/interference) is produced. Generally, at levels below the 6 dB SINAD, the systems will be considered as totally unusable.

The SINAD method has the advantage of evaluating the entire receiver, including the audio section. The modulating signal usually taken for this measurement is a 1 kHz audio tone. Thus, if the receiver produces harmonic distortion of the 1 kHz tone, the distortion products remain when the audio distortion analyzer rejects the 1 kHz fundamental signal, and the SINAD ratio decreases accordingly.

Because the SINAD method evaluates more thoroughly the characteristic of a receiver, this method is preferred over the quieting measurement. As a result, it has, over the last several years, come to be accepted internationally as the one generally used with FM land mobile communications equipments [114-117].

For these reasons, the SINAD method was also chosen in this study as the uniform sensitivity evaluation method. The measurement procedure is well defined for FM and SSB, but not for ACSSB. A suggested method for ACSSB will be defined in section 3.2, and the 12 dB SINAD level of the various systems under test will be measured. The 20 dB quieting values will also be measured for these systems, in order to show some additional problems that preclude the use of this method for comparative evaluation purposes.

2.3 INTERFERENCE CRITERIA

In this section, the necessary background required for an interference analysis between systems is given. A number of terms are defined, and their application to this study is explained. The role of the protection ratios as a tool in determining the susceptibility of a system to interference is explained. The objective and subjective interference criteria used to measure the protection ratios are described. A practical application of the protection ratios is brought by showing how it is used in interfering distance calculations, and a base-station to base-station example that will be used as our model to compare the systems under test is presented.

2.3.1 Transmission Interfering into a System and Other Definitions

2.3.1.1 ASSIGNED FREQUENCIES

The assigned frequency (F_a) is usually defined as the center frequency of the RF modulated waveform (center of the emitted spectrum). For FM, the assigned frequency is equal to the carrier frequency (F_c). For ACSSB, the assigned frequency is defined as the suppressed carrier frequency (F_{sc}) plus 1.8 kHz [118], where the suppressed carrier frequency is that radio frequency which would result in a frequency of zero hertz when fully translated by the receiver. This latter assigned frequency was chosen as being the center of a transmitted baseband of 300 Hz to 3.3 kHz. In the Canadian Department of Communications Radio Standard Specifications for SSB, RSS-125 [119], the assigned frequency is defined as: "*the center frequency of the band assigned to a station*", but as no specific bandwidth was assigned for ACSSB, the value suggested in reference [118] was chosen. The assigned frequency of SSB was taken as the one defined in the RSS-125, i.e., located 1.4 kHz above the suppressed carrier frequency. This is in conflict with its own definition, since the assigned channel spacing for HF SSB is 3 kHz, but, for performance comparison with the minimum requirements given in the RSS-125, 1.4 kHz was kept.

2.3.1.2 CO-LOCATED, ADJACENT, INTERSTITIAL, AND CO-CHANNELS

Once a channel spacing is set, the channels on each side of an assigned one are called adjacent channels. A channel located at only half the channel spacing is called an interstitial or offset channel. In the land mobile bands, adjacent FM channels can geographically be located relatively close (less than a mile) to each other (this is referred to as co-location), but

an interstitial FM channel is always geographically separated (by many miles) from the 2 stations between which it is assigned. Note that co-located stations are most of the time not excessively close to each other; co-location generally implies a certain small geographical separation, in the order of .3 to .9 miles. Co-located stations that are physically close to each other require special protection to limit the spread of their spurious emissions.

Considering the case of the tested FM systems, adjacent stations have their assigned frequency 30 kHz apart, while an interstitial station, inserted halfway between two adjacent stations will have its assigned frequency 15 kHz from them.

In summary, co-channel is used to designate 2 transmitters with the same assigned frequencies, adjacent channel, 2 transmitters with their assigned frequencies separated by one channel bandwidth, and interstitial or offset channel, 2 transmitters separated by half a channel bandwidth.

2.3.1.3 INTERFERENCE INTO A SYSTEM

When two modulated transmitters are stationed near enough to each other in frequency so as to cause partial or complete overlapping of their spectra in the receiver, interference results. The interference due to the other modulated transmitter may be divided into 2 broad classifications: co-channel interference arising from transmitters operating on the same channel, and adjacent-channel interference arising from transmitters operating on different channels. This classification is useful only when the channel spacing is well defined. In this study, the determination of a channel spacing for VHF SSB and VHF ACSSB is sought, so the level of interference (or protection ratio) for a range of interfering frequencies around an assigned frequency must also be found. Note that having this information also provides an estimation of the effects of an assigned frequency variation, due to oscillator drift, on the protection ratios of the systems under test.

A *system* consists of a transmitter and a receiver with their assigned frequencies both tuned to the same frequency. The transmitter and receiver in this case will be referred to as the on-channel transmitter or receiver. The transmitted signal will often be referred to in this case as the *desired* signal, and the received signal as the *on-channel* signal, but *on-channel*, *desired*, or *wanted* signal are used here freely as meaning the same thing. An *undesired* signal usually represents an intruder modulated transmission adjusted in frequency and power so as to interfere with the on-channel signal; *undesired*, *unwanted* or *interfering*

signal are used here freely as meaning the intruder transmission. The propagation medium through which the waveform is transmitted will be referred to as a *link*.

2.3.1.4 DESIRED AND UNDESIRED SIGNAL LEVEL

The desired signal level is the power level of the wanted transmitted signal present at the on-channel receiver input, whereas the undesired signal level is the power level of the interfering signal present at the input. Both power levels are given in dBm. The power level and frequency of the desired signal are usually fixed and do not change during a set of measurements, but the power level and frequency of the interfering signal change: this power level is usually increased until it produces a specified degradation of the demodulated audio at the on-channel receiver output; this is repeated for a certain number of interfering frequencies in the vicinity of the on-channel assigned frequency.

2.3.1.5 FREQUENCY SEPARATION

The frequency separation is the separation in hertz between the assigned frequencies (F_a) of the desired and undesired signals.

2.3.1.6 OTHER DEFINITIONS

FM into FM means an FM transmission interfering into an FM system.

FM into ACSSB means an FM transmission interfering into an ACSSB system.

ACSSB into ACSSB means an ACSSB transmission interfering into an ACSSB system.

ACSSB into FM means an ACSSB transmission interfering into an FM system.

The same definitions apply to SSB, changing ACSSB to SSB.

2.3.2 Protection Ratios

2.3.2.1 GENERAL CONSIDERATIONS AND DEFINITIONS

The susceptibility of a system to interference is determined by its protection ratio. The protection ratio is usually defined as the power ratio (in dB) of the wanted (desired) signal to the unwanted (interfering) signal at the input of the receiver, which yields at its output the demodulated wanted signal, with a specified degradation. Two general interference criteria, objective and subjective, are used to determine signal degradation.

A commonly used objective measurement process in communications is the SINAD method. As seen, the 12 dB SINAD measurement is also used in the evaluation of the

receiver's sensitivity. In the latter case, it is the receiver noise that constitutes the interference. When used in interference susceptibility measurements, the interference is another modulated signal rather than the receiver noise. The use of objective techniques implies that the results will be independent of the observer, which is highly desirable.

The subjective method involves a determination, by listeners, of the intelligibility of voice signals in a specified interference environment. The interfering signal is usually modulated with a voice signal that is independent of the wanted signal. The different voices help listeners to differentiate between the wanted signal and the interference.

In each method, the required protection ratio which is observed depends on the chosen quality measure. For example, in the objective SINAD method, a 12 to 6 dB SINAD degradation will require a smaller protection ratio than the one obtained with a 15 to 12 dB SINAD degradation. Similarly, in the subjective method, a criteria measure of "disruptive interference" will require a smaller protection ratio than the one of the "just noticeable interference" criteria. In addition, in subjective tests, the size, nature, composition, and degree of training of the listener panel may also influence the results.

Desired to Undesired (D/U) level or Ratio (DUR), On-channel to Interfering Ratio (OIR), or Carrier to Interference (C/I) Ratio (CIR) are various names used to describe the ratio of the on-channel signal to the interfering signal level. But protection ratio is restricted to that ratio that produces a specified degradation at the audio output of the on-channel receiver. For example, the disruptive protection ratio is the D/U ratio that will start to cause disruptive interference on the demodulated desired signal.

Because Interference to Carrier Ratio is a term that is descriptive for FM, but not for SSB or ACSSB (the carrier is suppressed for these modulation schemes) its usage in this study will be very limited.

The protection ratio in dB is calculated simply as the difference between the desired (wanted) and undesired (interfering) signals in dBm, at the input of the receiver. A protection ratio curve shows the protection ratio for various frequency separations. This curve effectively yields, for various frequency separations, the number of dB that an interfering signal must be – above or below the desired signal level – to produce a specified degradation (specified by the interference criteria) to the demodulated audio of the desired signal. When this degradation occurs with an interfering signal equal to the desired signal level, the protection ratio between the two signals is of 0 dB. Thus, the 0 dB line in a protection ratio curve

represent the on-channel (desired) signal level, and is usually referred to as the *reference level*. The interfering signal level that produced the specified degradation can be calculated by subtracting the protection ratio from the on-channel signal level.

For example (see Table 1), under a given interference criteria, for a desired signal level of -110 dBm, and an interfering one of -120 dBm, the protection ratio will be: $(-110) - (-120) = 10$ dB. Similarly, for a desired signal of -110 dBm, and an undesired one of -80 dBm, the protection ratio will be: -30 dB. Using the conventional definition of the protection ratios, the sign of the protection ratio is thus set so that a positive protection ratio means that, to produce the specified degradation, the interfering signal is weaker (i.e., has less power) than the desired signal, while a negative protection ratio means that the interfering signal is stronger. In the above example, for a "disruptive" protection ratio of 10 dB, any interfering signal equal or stronger than -120 dBm will produce disruptive interference on the on-channel receiver, while for a disruptive protection ratio of -30 dB, any interfering signal equal or stronger than -80 dBm will cause disruptive degradation.

Desired Signal Level (dBm)	Interfering Signal Level (dBm)	Protection Ratio (dB)	Relative Amplitude of Interference (dB)	Required Attenuation from a 25 Watts (44 dBm) TX (dB)
-110	-50	-60	+60	94
-110	-80	-30	+30	124
-110	-110	0	0	154
-110	-120	+10	-10	164

TABLE-1: Comparison of Various Protection Ratios
(for a given interference criteria)

2.3.2.2 INTERPRETATION OF THE PROTECTION RATIOS

Because of its importance, the significance of the protection ratios is emphasized: as an additional example, consider a frequency separation of 15 kHz between the assigned frequencies of the desired and the undesired stations, and a disruptive protection ratio measurement of -30 dB. This means that when the received interfering signal has a level 30 dB stronger (or more) than the received desired signal level, disruptive interference on the on-channel receiver will result. If the on-channel received signal level is -110 dBm, then, the interfering transmitter needs to be geographically separated by a distance large enough so that the interfering signal (when received by the on-channel receiver) will be attenuated to a level

lower than -80 dBm. If, for example, the interfering transmitter emits at a power of 25 watts (44 dBm), the required attenuation will then be given by the difference in dB between these two levels (i.e., $44 - (-80) = 124$ dB). The geographical separation distance that will produce such an attenuation can be found using propagation path-loss equations. Note that higher required attenuation leads to higher needed geographical separation. Calculations of required geographical distance between the tested systems will be made in this study. The path-loss equation used for the calculations is described in section 2.3.4.

Now, what is the effect of a larger protection ratio on the required geographical separation? Is a higher protection ratio better than a lower one? Is a lower relative amplitude of the interfering signal better or worse than a higher one? As one can see, a clear relationship between these various parameters would be useful. Using the example given in Table 1, one can conclude that:

- Larger or higher protection ratios mean lower relative allowed amplitude of the interfering signal, but higher required attenuation of the interfering transmitter, thus higher geographical separations. Then, higher protection ratios are worse than lower ones because more geographical separation from the interfering signal is required. Also, higher protection ratios will produce a wider or higher protection ratio curve. A comparative example of 3 protection ratio curves is given in figure 2.2.
- The worst protection ratio curve is the widest or highest one. The worst protection ratios are the largest ones.
- Smaller or lower protection ratios mean higher relative allowed amplitude of the interfering signal, but lower required attenuation of the interfering transmitter, thus lower geographical separations. Then, lower protection ratios are better than higher ones because less geographical separation from the interfering signal is required. Thus, the lower the protection ratio is, the better the receiver can resist to interference. Also, lower protection ratios will produce a narrower or lower protection ratio curve. (see figure 2.2).
- The best protection ratio curve is the narrowest or lowest one. The best protection ratios are the smallest ones.

FIGURE 2.2 : Comparison of Protection Ratio Curves

2.3.3 Subjective and Objective Interference Criteria

The interference criteria is a measure of the degradation caused by the interfering signal to the demodulated desired signal. In order to compare the applicability of the various interference criteria that have been used in the past for protection ratio measurements and to be able to find an objective criterion that can yield results similar to a subjective one, various criteria were used in this study. They are defined below.

2.3.3.1 SUBJECTIVE INTERFERENCE CRITERIA

1) Just Noticeable (J-N) Interference Criteria

The just noticeable interference, abbreviated "J-N", is defined as a barely detectable degradation in the desired demodulated signal; it would not be observed if the interfering signal was reduced slightly in level (1-2 dB). In this case, both the on channel and the interfering transmitters are modulated with voice.

2) Just Noticeable With No On-Channel Modulation (J-N-N-M) Interference Criteria

The just noticeable with no on-channel modulation interference, also abbreviated "J-N-N-M", "Just Not. N.M.", or "Just Noticeable N.M.", is defined as the just noticeable interference when no modulation (i.e., modulation = residual noise level) is applied at the input of the on-channel transmitter. The interfering transmitter is modulated with voice. Because there is no modulation on the on-channel system, the interference is detected earlier than in the just noticeable case.

3) Disruptive Interference Criteria

The disruptive interference is defined as a disturbing degradation which causes some words of the demodulated wanted signal to be garbled, requiring occasional repeated message transmissions. Both the on-channel and the interfering transmitters are modulated with voice.

2.3.3.2 OBJECTIVE INTERFERENCE CRITERIA

Two objective criteria under various on-channel and interference conditions were used in this study: The 12 to 6 dB SINAD degradation, and the 15 to 12 dB SINAD one. They will be described in more detail in section 3.3.

2.3.4 Path Loss and Interfering Distances

The interfering signal level can be translated into an equivalent transmitted power radiated at some distance. Using a propagation path-loss equation, a curve of the distances at which interference will occur as a function of channel separation can be drawn. Note that the use of the propagation loss equation in this study is not intended to provide an accurate figure of the real interfering distances, but rather to provide a comparative figure between the different tested systems.

Various statistical models exist to determine propagation losses in a number of different situations (e.g., [120-126]), but one that is commonly used to determine propagation losses over irregular terrain is that of Egli [120]. Because of the relatively low complexity of the Egli model, the model used in this study is based on it. Using the equation given in the FCC Spectrum Management Task Force paper [127], and a correction factor provided by the Regulation section of DOC, the calculation is based on the following equation:

$$RP = -120 + 20 \log_{10}(HT) + 20 \log_{10}(HR) - 40 \log_{10}(D) + 10 \log_{10}(P) - 20 \log_{10}(F)$$

where:

RP = Received power in dBWatts;

D = Distance in miles;

P = Transmitted power in watts;

F = Frequency in MHz;

HT = Transmitting antenna height in feet;

HR = Receiving antenna height in feet.

As the propagation loss equation used was given in terms of feet and miles, no change has been made to it, so that the interfering distances will be given in miles. To calculate the interfering distance, the equation is rearranged as follow:

$$D = \text{antilog}_{10} \left[\frac{-120 - RP + 20 \log_{10}(HT) + 20 \log_{10}(HR) + 10 \log_{10}(P) - 20 \log_{10}(F)}{40} \right]$$

where RP is the received power (dBW) of the interfering signal. As seen, the level of this signal can be obtained from the protection ratio curves.

The example that will be used throughout this study is based on the mobile radio model described in section 2.1 (Calculation of the spectrum efficiency), shown in figure 2.1. A mobile is transmitting to base 1. Another base, base 2, located some distance away, is

also transmitting. Considering the signal level of the mobile, as received by base 1, and considering the frequency separation of the two bases, how far should base 2 be located so that no interference (as per the interference criteria) occurs at base 1? In our context, the signal level of the mobile is the reference signal of the protection ratio curves, and it was assigned various values for the measurements. But if the smallest value is taken, the interfering distance of base 2 will be the farthest one. Considering that the 12 dB SINAD power level is about the minimum level for acceptable communications, this will be the value chosen, in the interfering distance calculation, for the signal level of the mobile as received by base 1 (i.e., as the reference level). This situation represents the case where the mobile is on the limit of its coverage area (radius d_c of figure 2.1-C).

Having chosen the signal level as received by base 1, the other parameters to be defined are:

- base 1 antenna height: 50 feet;
- base 2 antenna height: 50 feet;
- base 2 transmitted power: 25 watts;
- frequency: 150 MHz.

The fact that the interfering distances calculated in this study are just an estimation is emphasized again. But since the calculations will be done using similar conditions and criteria, the estimation can be used to compare the various systems. If extensive prediction programs with data base, such as the one used by SMS [128] or by the CRC prediction program [129] had been used, the calculated interfering distances would have been more realistic. But the use of a simpler model in this study has only one goal: to easily provide an estimation of the effects of the various parameters of a system on the spectrum efficiency. Protection ratios are abstract values, and as a means of comparing the different systems, a number such as "20 dB more protection ratio than the other" is not self explanatory. A comparison done in terms of interfering distances will more easily relate protection ratio and their effects on the various communication systems under test.

CHAPTER 3

EXPERIMENTAL EVALUATION

of FM, ACSSB, and SSB

3.1 EMITTED SPECTRUM

In this section, the emitted spectra of commercial VHF FM, ACSSB, and SSB are obtained under various modulation conditions. The results obtained are used to provide a better comprehension of the differences between the FM, ACSSB, and SSB transmission, and to help in determining appropriate channel spacing values for the SSB and ACSSB systems.

3.1.1 General Considerations and Units Under Test

3.1.1.1 GENERAL CONSIDERATIONS

The spectrum analyser used to obtain the emitted spectrum figures has a "MAX HOLD" trace facility which retains in memory and displays the largest signal level occurring at each horizontal data position over the repetitive sweeps. Using this facility, one can obtain the worst-case voice emitted spectrum of the transmitter: this can be done by either talking continuously into the microphone for one or two minutes or equivalently, by using an audio tape recorder on which voice is recorded. Another modulating signal that was experimented with is the use of an audio signal generator, but discussion of the results obtained with this instrument is deferred until section 3.4. The spectrum obtained with the MAX HOLD function does not represent the instantaneous level of emission, but rather shows the maximum reached over a few minutes of operation. This voice modulated spectrum thus represents the long time, worst-case or widest spectrum that the unit delivers, and will be used as a means of comparison between the various forms of modulation.

Caution should be exercised in comparing the various emitted spectrum figures: the width of the shown frequency component as well as the noise floor in figures obtained using a spectrum analyser vary as a function of the resolution bandwidth. The difference in dB in the noise floor measured with various resolution bandwidths is given by [130]:

$$\text{dB} = 10 \log (\text{Resolution Bandwidth 1}) - 10 \log (\text{Resolution Bandwidth 2}).$$

For example, the noise floor seen with a resolution bandwidth of 300 Hz is 10 dB higher than it would be if it was taken with a resolution bandwidth of 30 Hz [i.e., $10 \log (300) - 10 \log (30) = 10 \text{ dB}$]. Note also that the carrier to noise ratio in a 1 Hz bandwidth can be calculated using the emitted spectrum figures and the above equation.

3.1.1.2 UNITS UNDER TEST

Three different systems, the Motorola MCX 100, the FORCE Communications UNIDEN AMH 350, and the ICOM IC-251 A/E (in FM mode) were used as the Frequency Modulation transceivers. The Sideband Technology (STI) Pioneer 1000 was used for the ACSSB system. The ICOM IC-251 A/E in the SSB mode was used for the SSB system. These units will generally be respectively referred to as the MCX-FM, the FORCE-FM, the ICOM-FM, the STI-ACSSB, and the ICOM-SSB. But abbreviations to the MCX, FORCE, STI or ACSSB, and SSB are also used. Rated power of these units are: 30 Watts average for the MCX, 35 for the Force, and 10 for the ICOM-FM, 25 Watts PEP (peak envelope power) for the STI, and 10 for the ICOM-SSB. Appendix A contains a copy of the specifications provided by the manufacturers. Pilot-based SSB systems (and ACSSB) are described in more detail in Appendix D.

All units were designed to operate in the VHF frequency band. Some units were restricted to operating frequencies around 150 MHz. Note that FM units that operate in the VHF band must comply with the Canadian Radio Standard Specifications (RSS), in this case, the RSS-119 [117]. The allocated channel spacing for FM units in this band is 30 kHz. The MCX and the FORCE are typical land mobile units whereas the ICOM is a radio amateur unit with choice of modulation (FM or SSB); in its FM mode, it was designed to comply with the RSS-119.

The manufacturer's suggested channel spacing for both SSB and ACSSB is 5 kHz. Since there is no Radio Standard Specification for the specific operation of SSB or ACSSB systems in the VHF band, no appropriate regulation exists that limits the level of emission within such a channel spacing. On the other hand, the Canadian Department of Communications suggests to use the RSS-125 [119] as a guideline for SSB usage in the other frequency bands: "*Where SSB is used above 30 MHz, RSS-125 is used as a guide*" [131]. Therefore, some manufacturers have used in the past guidelines similar to the ones provided by the RSS-125 as a baseline to design 5 kHz channel spacing systems. Unfortunately, this radio standard is made for the 3 kHz channel spacing SSB operating in the HF band, and might not be appropriate for the VHF band. One of the purposes of this study is to use the properties of the actual FM VHF systems, and try to determine if 5 kHz is appropriate for the commercial SSB and ACSSB systems, and if it is not appropriate, to suggest guidelines that would permit stations to function properly within such a restricted channel spacing, and permit the co-existence of the new technologies with the 30 kHz FM one.

3.1.2 FM Transceivers

As shown in communications theory textbooks, the average power of a (constant envelope) frequency modulated signal is independent of the modulation. When no modulation is present, the carrier is emitted at the rated power level of the FM unit. When modulation is present, the carrier and side frequencies levels vary with the amplitude and frequency of the modulating signal, but the total average power contained in the modulated waveform remains constant.

Consequently, when no modulation is applied at the input of the transmitter, only a single RF tone (the carrier) at a power level equal to the rated level of the transmitter is present at the output. A typical emitted spectrum³ of this situation is shown in figure 3.1. Figure 3.1 was obtained using the FORCE-FM unit, which transmits at a constant power of 35 watts (45.44 dBm). Similar spectra (but with different power level) are emitted by the MCX FM and the ICOM-FM. Note that the dynamic range of the utilized spectrum analyser is 100 dB.

³ All the power spectrum figures of this study originated from the image observed on the spectrum analyser and transferred to the mainframe computer. The data was rescaled to the real power level that would be observed at the output of the transmitter, by adding to the ordinate axis the amount of external attenuation inserted between the transmitter and the spectrum analyser.

Figures 3.2 and 3.3 show the emitted spectrum of the MCX FM unit when its input is modulated with a 1 kHz audio tone. The amplitude of the modulating tone was adjusted so that the FM deviation was respectively about 3 and 4.5 kHz. The 3 kHz deviation value was chosen because it is the value used in the RSS-119 for the interfering channel in the two signal selectivity protection ratio measure. The 4.5 kHz one because it represents a maximum deviation that is rarely exceeded in the normal operation of these units. Note that this unit transmits at a constant power of 30 Watts (44.77 dBm).

Figure 3.4 shows an example of the use of the audio recorder to obtain the worst case (or long-time) voice emitted spectrum of this unit. The level of the audio signal was adjusted so that the maximum frequency deviation would not exceed 4.5 kHz. This maximum value was determined as being the deviation at the output of the transmitter that is rarely exceeded when one talks continuously into the microphone of this unit. The same maximum deviation was also obtained for both the FORCE-FM and ICOM FM units. The spectrum analyser recorded the power spectrum peaks (Max Hold function) at the output of the transmitter for about 5 minutes.

In figures 3.2 and 3.3, the total average power is shared between the sideband and the carrier frequency, and the average rated power of the transmitter could only be found by adding the power contribution of the various frequency components. But in figure 3.4, the rated output power can readily be found as being the maximum level displayed in the figure, since when a silence occurs in the voice modulating signal, only the carrier at the rated power level of the transmitter is present. The advantage of recording the peaks for a few minutes while the unit is voice modulated becomes apparent: the resulting displayed spectrum shows the range of maxima that will never be exceeded under normal operating conditions.

In order to show how the RF noise level decreases as a function of the frequency separation, figure 3.5 displays the same transmission as the one of figure 3.4, except that the span was increased to 1 Mhz. It shows the transmitter noise level relatively far, in frequency, from the assigned frequency of the FM station.

In order to compare the emitted spectra produced using the same frequency deviation (i.e., 4.5 kHz), but different modulation, the spectrum obtained using long time voice modulation (figure 3.4), the one produced using an audio noise generator, and the one produced using a 1 kHz tone modulation (figure 3.3) were superimposed and shown in figure

3.6. One can see that the 1 kHz tone modulating signal yields a spectrum that is noticeably lower than the long-time voice one around the center (assigned) frequency, but that follows it closely in the sloped regions. Note that the differences in the noise floor outside the assigned channel of these 2 spectra is caused, as mentioned earlier, by (unfortunately) using different resolution bandwidths on the spectrum analyser. The spectrum produced by the audio noise generator will be discussed in more detail in section 3.4, but one can readily note that the emitted spectrum obtained with it is very similar to the long-time voice one.

A long-time voice emitted spectrum was also obtained for the FORCE-FM and the ICOM-FM units. The rated power of these 2 units is respectively 35 and 10 Watts (45.44 and 40 dBm). Noting that the FORCE-FM unit is 5 watts higher in power than the MCX-FM unit, and that the ICOM FM is 20 watts lower, one could compare the worst-case emitted spectrum of the three FM systems. This is done in figure 3.7 where a correction factor of respectively -0.67 and +4.77 dB was added to the FORCE-FM and ICOM-FM spectrum curves to normalize them to 30 watts. One sees that the long-time voice emitted spectra of the 3 FM units are very similar. Since the comparison was made using the same resolution bandwidth, one observes that the transmitter noise level of the FORCE-FM outside the channel bandwidth is slightly higher than the one of the two other systems.

From these long-time voice modulated emitted spectra, one can see that the relative average power of the frequency components outside the FM assigned channel spacing is about 70 dB below the maximum power. The RSS-119, using a *“2500 Hz modulating signal at an input level 16 dB greater than that required to produce ± 2.5 kHz deviation at 1000 Hz”* requires, as a minimum performance standard, that *“the power in either adjacent channel shall be the lesser of 60 dB below the “on” channel or 50 micro-watts”*, where the adjacent channel power is defined as *“that part of the total power output of a transmitter, under defined conditions of modulation, which falls within a 16 kHz bandwidth, centered 25 kHz from the carrier frequency.”* This power measurement is further complicated by the need of a special adjacent channel power measuring apparatus comprising a mixer, filter, linear amplifier, RMS power meter, and a low noise signal generator.

Since the tested units comply with the standard, a simpler rule, such as *“the relative average power of the frequency components outside the assigned channel spacing shall be 70 dB below the rated on-channel power”* will be used as the comparative criteria in this study. In order to simplify this expression, the above statement can be referred to with a

term usually used for filters: the " x " dB bandwidth. Hence, one could say here that the 30 kHz channel spacing is based on the "70 dB bandwidth of the emitted spectrum". This expression will be used in this study.

In figure 3.8, the worst-case voice emitted spectrum of the MCX-FM is shown repeated every 15 kHz. Considering the case of two FM transmitters with their assigned frequency 30 kHz apart (i.e., adjacent channel situation in the VHF band), one can clearly see that for this type of FM system, the level of the interference from the adjacent station is about 70 dB below the maximum power of the desired station. This value goes down to about 30 dB for the interstitial channel situation.

RES BW 30 Hz
VBW 30 Hz
SWP 100 sec
CENTER 144.95986 MHz
SPAN 50.00 kHz

FORCE-FM; Ch #3
NO MODULATION
MAX HOLD 4 SCANS

FIGURE 3.1 : FORCE-FM Transmitted Spectrum; No Modulation

RES BW 100 Hz
VBW 100 Hz
SWP 10 sec
CENTER 144.96005 MHz
SPAN 50.00 kHz

MCX UNIT; Ch # 3
MOD 1kHz @ 3kHz DEV.
MAX HOLD FOR 1 MINUTE.

FIGURE 3.2 : MCX-FM Tx Spectrum; 1 kHz tone, app. 3 kHz deviation

RES BW 100 Hz
VBW 100 Hz
SWP 10 sec
CENTER 144.94515 MHz
SPAN 50.00 kHz

MCX UNIT; CH # 2
MOD 1 kHz @ 4.5 kHz Dev.
MAX HOLD FOR 2 MINUTES

FIGURE 3.3 : MCX-FM Tx spectrum; 1 kHz tone, app. 4.5 kHz dev.

RES BW 300 Hz
VBW 300 Hz
SWP 1.0 sec
CENTER 144.94515 MHz
SPAN 50.00 kHz

MCX UNIT - VOICE MODULATION
MAX PEAK DEV=4.5 kHz, CH #2
MAX HOLD for 5 Minutes

FIGURE 3.4 : MCX-FM Tx spectrum; Long-Time Voice modulation

RES BW 300 Hz

VBW 300 Hz

SWP 20 sec

CENTER 144.960 MHz

SPAN 1.000 MHz

MCX UNIT - VOICE MODULATION

MAX PEAK DEV=4.5kHz; CH #3

MAX HOLD FOR 5 MINUTES

FIGURE 3.5 : MCX-FM Long-Time Voice; 1 MHz Span

FIGURE 3.6 : MCX-FM; Noise, Tone, and Voice comparison

FIGURE 3.7 : MCX-FM, FORCE-FM, and ICOM-FM Normalized, Voice

FIGURE 3.8 : MCX-FM Long-Time voice; 3 stations

3.1.3 ACSSB Transceivers

As seen from modulation theory, a major difference between the exponential (FM) and linear modulation (SSB & ACSSB) schemes is that the spectrum of the former is emitted at a constant average power level, whereas the emitted average power of the linear modulation varies as a function of the level of the modulating signal. Consequently, the output power of an ACSSB system, for example, can not be rated in terms of constant average power as is FM. Instead, the power value used to rate the system is based on the maximum short-time average power that the unit delivers, and is referred to as the rated Peak Envelope Power (PEP) [130] [132]. Examples of calculations of the various power for FM, AM, and SSB are shown in figure 3.9. One sees that the Peak Envelope Power is a short-time average power, computed at the maximum amplitude level of the envelope of the signal, and that in the case of a constant envelope waveform, the PEP is equal to the average power. In terms of radio standard, PEP is defined as *"the average power developed by a transmitter during one radio frequency cycle at the highest crest of the modulation envelope"* [119]. Consequently, the PEP is a measure of the maximum attainable average power of a waveform that does not have a constant envelope.

Theoretically, the modulated bandwidth of ACSSB and SSB is the same as the modulating signal bandwidth; that is, in theory, the modulated signal is a simple direct frequency translation of the baseband signal. But, as will be seen in this and the next section, the real life situation is quite different because of the non-ideal characteristics of the linear power amplifier.

A feature of the STI-ACSSB unit is that the pilot frequency is transmitted at rated PEP (25 watts -44 dBm) for 250 ms every time the push-to-talk button is activated; this way, the receiver's automatic frequency control can lock-on the pilot frequency before the modulating signal is transmitted. For test purposes, this 250 ms delay can be extended indefinitely with a push-button included in the unit. Figure 3.10 shows the spectrum of this transmission, and was obtained using the *push*-button facility. Note that the pilot in this system is an above band pilot, located at 3.1 kHz above the suppressed carrier frequency.

In this and the following ACSSB emitted spectrum figures, the center frequency is the assigned frequency (already defined as the suppressed carrier frequency plus 1.8 kHz). Thus, looking at the center frequency, the suppressed carrier is located at a relative frequency of

-1.8 kHz, the 3.1 kHz above band pilot is at +1.3 kHz, and a 1 kHz modulated tone would be at -0.8 kHz.

Figure 3.11 shows the spectrum at the output of the transmitter (after the 250 ms delay), for the case where there is no modulation at the microphone input. The modulating signal is the internal noise of the audio section of the transmitter. The pilot tone dropped by about 8 dB (to 36 dBm), and the small peak located at -1.8 kHz is the suppressed carrier (about -7 dBm, or about 51 dB below rated PEP). Between these two peaks is the residual noise of the audio bandwidth.

Even at this low power level of about 4 watts (36 dBm), intermodulation between the pilot and the audio noise is readily apparent, and can be seen in figure 3.11 at frequencies above the pilot frequency.

Figure 3.12 shows the transmitted spectrum as observed at the antenna output when a 1 kHz audio tone is applied at the microphone input at a level that produces 25 watts PEP output. The peaks called "1 kHz" and "pilot" in this figure refer respectively to the RF translated 1 kHz modulating tone and the pilot frequency. Using the fact that these two peaks are 12 dB apart, the PEP (44 dBm) can be found as being about 2 dB above the 1 kHz RF tone average power level (42 dBm) shown on this figure. This is demonstrated in appendix C. Also from appendix C, the total average power of this signal is found to be about 17 watts. The resulting 12 dB difference between the RF 1 kHz tone and the RF pilot tone when the ACSSB unit is transmitting at rated PEP also plays an important role in the receiver's sensitivity measurements. This will be seen in section 3.2.

What impresses one when looking at this figure is the extent of the intermodulation products. The intermodulation between the 1 kHz modulated tone and the pilot produces the high peaks across the figure: intermodulation products of the third order have been identified in figure 3.12 as IM3, the fifth order as IM5, and the seventh order as IM7. The third order product is only about 32 dB below rated PEP; the fifth and seventh order are respectively about 60 and 80 dB below rated PEP. As can be seen, the extent of the intermodulation products outside an allocated 5 kHz bandwidth is quite high.

In passing, a spurious frequency is seen between the RF translated 1 kHz tone and the pilot. This spurious is a 2 kHz tone, an audio harmonic generated internally (in the audio stage) by these units. Naturally, its presence also produces intermodulation products. The

combination of the 2 kHz spurious and the pilot frequency, for example, yield the products that are seen between the pilot and IM3, and between IM3 and IM5.

It can be noticed that the level of the pilot in figure 3.12 has decreased by about 7 dB relative to its level in the unmodulated case shown in figure 3.11. As can be seen in Appendix D, this design feature referred to as "pumping", was suggested by Lusignan [6 7] [13] to reduce the level of the intermodulation products. Pumping effectively reduces the pilot level as the wanted audio signal increases, and has a beneficial effect in reducing the intermodulation, but it already seems that only an improved linear power amplifier will noticeably reduce the intermodulation products.

Radio Standard RSS-125 defines maximum values of emitted intermodulation products for SSB transmitters operating in the HF bands. In this specification, a two-tone signal modulates the transmitter, and resulting values of the odd-order intermodulation products are used for the performance standard. Although the tested ACSSB units operate in the VHF band, it is interesting to see if, at least, they follow the minimum performance standard required by the HF standard. From the RSS-125 one gets that the third, fifth, and seventh order intermodulation products must be confined to 31 dB below rated PEP, the ninth, eleventh, and thirteenth order products 38 dB below, and all other spurious, outside a ± 8 kHz band centered on the assigned frequency must be 46 dB below rated PEP. Looking at figure 3.12, one sees that this ACSSB unit conforms easily to these limits.

Figure 3.13 shows the same transmission as in figure 3.12, but using a span of 1 MHz. Note that the two spurious frequencies at about 250 kHz away from the assigned frequency, are more than 75 dB below PEP. These are particular to these units and are design related. Except for these, this figure is similar to the one of the 1 MHz span emitted spectrum of the MCX FM (figure 3.5).

Figure 3.14 shows the worst-case voice emitted spectrum for these units. Recall that for this measure, only the maximum levels of the transmitted spectrum are retained when the modulating voice signal from the tape recorder is fed into the microphone input. The level of the voice modulation was adjusted so that the PEP would rarely exceed 25 Watts; this corresponds to the level that was rarely exceeded when one is talking continuously into the microphone input.

The RF modulated voice signal ranges from a relative frequency of about -1.6 kHz (which is about 200 Hz modulated) up to about +0.9 kHz (2.7 kHz modulated); the pilot is

at 1.3 kHz (3.1 kHz modulated). The spectrum around these limits drops sharply for about 30 dB, and the third order intermodulation products (around the 0 dBm line) are found about the +2 to +4 kHz and the -2 to -4 kHz range. At the end of coverage of the third intermodulation products, another drop occurs, and the spectrum is dominated by the fifth order products. From then on, the spectrum drops slowly to its noise level (about -50 dBm in this 100 Hz resolution bandwidth) within about ± 12 kHz (not shown in this figure).

In order to better visualize where the ACSSB emitted spectrum would cross over into the adjacent channel should it be assigned a specific channel spacing, figures 3.15 to 3.18 show the long-time voice spectrum of the STI-ACSSB (figure 3.14), repeated at the center, and at respectively plus and minus 5, 7.5, 10, and 13 kHz. The figures show that, with channel spacing of 5, 7.5, 10, and 13 kHz, the spectrum of adjacent channels meet at respectively about 40, 45, 66, and 70 dB below PEP. One can notice the sharp dB drop between the 7.5 kHz and the 10 kHz channel spacing values (i.e., from 45 to 66 dB for an increase of 2.5 kHz spacing) as being the effect of moving out of the third intermodulation products and getting into the fifth order ones. One also notes that more generally, if the level of intermodulation products was lowered (i.e., the linearity of the power amplifier improved), the dB below PEP would substantially be better at these channel spacings.

One can compare these long-time voice emitted spectrum with the one obtained for the FM units (figure 3.8). The FM units have been assigned by a radio standard a 30 kHz channel spacing, and it was seen that at the limits of this assigned bandwidth the spectrum was down the maximum (rated) power by about 70 dB. If the same criteria for defining the channel spacing, i.e., the frequency at 70 dB below the rated PEP, is applied to ACSSB, then its required channel spacing, from figure 3.18, would be about 13 kHz! Should 35 dB below PEP be acceptable, the limit would decrease to less than 4 kHz, and with 66 dB down it would be about 10 kHz (figure 3.17).

For comparison purposes, figure 3.19 displays the emitted spectra obtained with the long-time voice (figure 3.14), the 1 kHz tone modulation (figure 3.12), and an audio noise generator. Note that as for FM modulation, the spectrum obtained with the audio noise generator is very similar to the one obtained with the long-time voice. Also from this figure one can see that the worst-case spectrum obtained with the voice does not excessively differ from the general shape that could be extrapolated from the spectrum obtained with only one modulating tone. The spectrum obtained when the unit is modulated with a single 1 kHz

modulating tone exceeded, at a couple of places, by just a few dB, the long-time voice one. The use of a single modulating tone to characterize the ACSSB spectrum has been generally opposed in the past [100], mainly based on the argument that single tone transmissions are not encountered in voice modulation, and hence can not be used to represent the typical voice modulated emitted spectrum of ACSSB. This figure shows that this is partially true, but that the difference is not excessive. Should certain forms of digital modulation be used with these units, the single or multiple tone spectrum could certainly not be ignored. Nevertheless, since the systems under test in our case are used for voice modulation, the long-time voice emitted spectrum is a more appropriate method of comparison.

FIGURE	MODULATION TYPE	TIME DOMAIN	FREQUENCY DOMAIN C = CARRIER (C) = SUPPRESSED CARRIER	SHORT TIME AVERAGE (HEATING) POWER (WATTS)	LONG TIME AVERAGE (HEATING) POWER (WATTS)	MODULATED PEV (VOLTS)	PEAK ENVELOPE POWER PEV_{rms}^2 / R (WHERE $PEV_{rms} = PEV / \sqrt{2}$) (WATTS)
A	CONSTANT WAVE (CW)			$\frac{V_C^2}{2R} = 100$	$\frac{V_C^2}{2R} = 100$	100	100
B	AM 1 TONE 100% MODULATION			VARIES AS A FUNCTION OF VOLTAGE	$\left(1 + \frac{m_a^2}{2}\right) \frac{V_C^2}{2R} = 150$	200	400
C	AM 1 TONE 73% MODULATION			VARIES AS A FUNCTION OF VOLTAGE	$\left(1 + \frac{m_a^2}{2}\right) \frac{V_C^2}{2R} = 127$	173	300
D	SSB 1 TONE			$\frac{V_C^2}{2R} = 100$	$\frac{V_C^2}{2R} = 100$	100	100
E	SSB 2 EQUAL TONES			VARIES AS A FUNCTION OF VOLTAGE	$\frac{V_C^2}{2R} + \frac{V_C^2}{2R} = 200$	200	400
F	SSB VOICE			VARIES AS A FUNCTION OF VOLTAGE (i.e. VOICE MODULATION)	VARIES AS A FUNCTION OF VOLTAGE (i.e. VOICE MODULATION)	100	100
G	FM 1 TONE			$\frac{V_C^2}{2R} = 100$	$\frac{V_C^2}{2R} = 100$	100	100

$R = 50 \text{ ohms}$ PEV = PEAK ENVELOPE VOLTAGE $PEV_{rms} = PEV / \sqrt{2}$
 V_C = CARRIER (OR SUPPRESSED CARRIER), ARBITRARILY CHOSEN AT 100 VOLTS PEAK IN ALL EXAMPLES
 FOR AM: m_a = MODULATION INDEX: e.g. 73%, $m_a = 0.73$, $V_{mod} = 1 \text{ V}$

V_m , V_1 , V_2 = MODULATING VOLTAGES = 1 VOLT

FIGURE 3.9 : AVERAGE AND PEAK ENVELOPE POWER FOR VARIOUS MODULATION SCHEMES

RES BW 30 Hz
VBW 30 Hz
SWP 50 sec
CENTER 144.94800 MHz
SPAN 20.00 kHz

STI-ACSSB; CH #3
PILOT PUSH BUTTON; 25 W.
MAX HOLD for 3 SCANS

FIGURE 3.10 : STI-ACSSB Transmitted Spectrum, Pilot Only

RES BW 30 Hz
VBW 30 Hz
SWP 50 sec
CENTER 144.94750 MHz
SPAN 20.00 kHz

STI UNIT: CH#3
NO MODULATION
MAX HOLD for 2 SCANS

FIGURE 3.11 : STI-ACSSB transmitted spectrum, No Modulation

RES BW 30 Hz
VBW 30 Hz
SWP 75 sec
CENTER 144.94750 MHz
SPAN 30.00 kHz

STI-ACSSB CH #3
MOD=1kHz; 25 WATTS PEP
MAX HOLD for 4 SCANS

FIGURE 3.12 : STI-ACSSB Tx spectrum, 1 KHz tone, 25 Watts PEP

RES BW 300 Hz
VBW 300 Hz
SWP 20 sec
CENTER 144.948 MHz
SPAN 1.000 MHz

STI-ACSSB, CH #3
MOD=1kHz @ 25 WATTS PEP
MAX HOLD for 3 SCANS

FIGURE 3.13 : STI-ACSSB Tx spectrum, 1 kHz tone, Span 1 MHz

RES BW 100 Hz
VBW 100 Hz
SWP 5.0 sec
CENTER 144.84690 MHz
SPAN 20.00 kHz

STI-ACSSB; CH #3
MOD=VOICE, PEP MAX = 25 W
MAX HOLD 2 MINUTES

FIGURE 3.14 : STI-ACSSB Tx spectrum, Voice, 25 Watts PEP

FIGURE 3.15 : STI-ACSSB Tx spectrum, Voice - 5 kHz Channels

FIGURE 3.16 : STI-ACSSB Tx spectrum, Voice - 7.5 kHz Channels

FIGURE 3.17 : STI-ACSSB Tx spectrum, Voice - 10 kHz Channels

FIGURE 3.18 : STI-ACSSB Tx spectrum, Voice - 13 kHz Channels

FIGURE 3.19 : STI-ACSSB Tx Spectrum, Voice, Tone, and Noise

3.1.4 SSB Transceivers

The ICOM transceivers provide an SSB mode. It can be switched to upper SSB or lower SSB. The upper SSB mode was used for all the tests in this study. The rated PEP of these unit is 10 watts (40 dBm).

In theory, no RF signal should be emitted from a suppressed carrier single sideband transmitter when no modulation is present at its input, but as seen in figure 3.20, in practice, the emitted spectrum under this condition contains the attenuated suppressed carrier and the residual baseband noise produced by the unit. Recall that, by definition, the assigned frequency of SSB is located 1.4 kHz above the suppressed carrier. Accordingly, looking at the center frequency, the suppressed carrier is located at a relative frequency of -1.4 kHz, and a 1 kHz modulated tone will be at -0.4 kHz. In this unit, the suppressed carrier is only about 33 dB below the rated PEP.

Figure 3.21 shows the emitted spectrum when the input is modulated with a single 1 kHz audio tone, at a level adjusted to produce 10 watts PEP (the rated peak envelope power). One notes that in the case of a single output tone, the PEP is equal to the average power (the contribution of the suppressed carrier being very small). Because there is only one strong signal, practically no intermodulation is present. The non-linearity of the linear power amplifier becomes obvious only when two or more tones are used to modulate the input of the transceiver. With two tones, one of 850 Hz and one of 1950 Hz, applied at the input of the transmitter and adjusted as to produce rated PEP (10 watts) with equal modulated RF components, one observes that the intermodulation products outside an arbitrary 5 kHz band are about 44 dB below the rated PEP (figure 3.22). Note also the relatively high level 1100 Hz audio spurious signal internally generated.

The above two-tone test was done using the parameters specified in the RSS-125, and as for the ACSSB unit, the ICOM-SSB unit conforms to this RSS minimum performance standard, and therefore could be used in a 3 kHz channel spacing at HF.

In order to simulate a transmission with a pilot tone (i.e., similar to the STI-ACSSB), a two-tone test using a 1 kHz and a 3.1 kHz tone was also done. The input level of the two tones were adjusted as to produce a 12 dB difference at the output of the transceiver, with the PEP kept at the rated level (10 watts). The transmitted spectrum is shown in figure 3.23, and a comparison with the ACSSB spectrum (figure 3.12) is shown in figure 3.24. In figure 3.24, the ICOM SSB spectrum (of figure 3.23) was raised by 4 dB [the difference between

10 watts (40 dBm) and 25 watts (43.98 dBm)] in order to compensate for the difference in power between these two units. Note also that the width of the frequency components and the noise floor are not significant in this comparison, since the spectra were unfortunately taken with 2 different resolution bandwidths. Nevertheless, the figure shows a higher level of third order intermodulation products for the STI-ACSSB, but a significantly lower level of the higher order products. Note also the difference between the 2 spectra due to the lower internally generated 2 kHz harmonic of the ACSSB unit. Another comparison between these two units is provided below, with voice modulation.

Figure 3.25 shows the long-time voice spectrum for this unit, and figure 3.26 shows this spectrum superimposed to the one obtained with the two tones modulation. As for ACSSB, the spectrum produced by the 2 tones modulation exceeds, at a few places, the one produced by the long-time voice one, but the general shape could be considered similar. Also added to figure 3.26 is the spectrum obtained when an audio noise generator is used as the modulating signal. Again, it can be seen that this spectrum is similar to the one obtained with the long-time voice modulation.

In figure 3.27, the long-time voice spectrum of the ICOM-SSB (figure 3.25) and of the STI-ACSSB (figure 3.14) are compared. Again, to compensate for the difference in power of the two units, the ICOM-SSB spectrum (of figure 3.25) was raised by 4 dB. As in figure 3.24, the assigned frequency of the SSB was slightly shifted so that the suppressed carrier were made about equal. A 100 Hz resolution bandwidth was used for the 2 spectra.

The figure shows that the 2 spectra are very similar. The presence of the pilot in the ACSSB makes the audio bandwidth larger, but it does not seem to produce an adverse effect on the rest of the spectrum. This is probably due to the implementation of pilot pumping in the ACSSB units and seems to effectively have a beneficial effect in reducing the intermodulation for high level modulating signals.

The noise level outside the channel bandwidth is slightly higher for SSB than for ACSSB. The average power level of the high frequency of the audio bandwidth is slightly lower for SSB than for ACSSB, probably due to the pre emphasis present in the ACSSB unit, but not in the SSB one. Also, as seen in the previous figures, the maximum average power displayed for the long-time voice signal of the SSB unit was about 8 dB below rated PEP. For ACSSB, it was about 4 dB. This difference is probably due to the effect of companding in ACSSB, which is effectively supposed to reduce the peak to average power ratio.

Basically, one can see that there are no major differences between the SSB and ACSSB spectra, so it can be concluded that no significant improvement regarding the intermodulation distortion caused by the non-linearities of the power amplifier has been made for the STI-ACSSB transmitters. The "70 dB below rated power" criteria used for FM, applied to SSB, would yield slightly larger required channel spacing than for ACSSB: of the order of 15 kHz, as seen from figure 3.25. At 10 kHz channel spacing, the spectra would touch at about 60 dB below the rated PEP. Finally from figure 3.28, one sees that, when the spectra of the long time voice modulated ICOM-SSB are spaced 5 kHz apart, they crossed at about 40 dB below PEP. This is the same value as the one obtained for the ACSSB units.

3.1.5 Interstitial ACSSB in FM Channels

As mentioned before, a suggested immediate implementation of ACSSB in the VHF bands would be to insert ACSSB channels between the presently allocated FM channels. In order to visualize this situation, a figure showing the long-time voice spectrum of 2 adjacent MCX-FM (30 watts average) channels and of one interstitial STI-ACSSB (25 watts PEP) was produced (figure 3.29). The spectrum of the STI unit crosses the FM one at about 50 dB below the maximum average power of the MCX. This value goes down to about 40 dB when 2 ACSSB stations, spaced 5 kHz apart, are inserted between the MCX-FM (figure 3.30). Recall that the value found previously for interstitial FM was about 30 dB. Consequently, it looks from these results that even only one interstitial ACSSB station would cause too much interference on the FM for them to be co-located. On the other hand, less geographical separation would be required for an interstitial ACSSB compared to an interstitial FM.

This figure can also be used in order to predict the levels of the intersection that would be found if a smaller bandwidth emitted spectrum technology was inserted at the interstitial frequency of the FM systems. For example, if a hypothetical 5 kHz, 70 dB bandwidth, ACSSB system was inserted between the 2 FM, it can be deduced from figure 3.29 that the spectrum of such a system would meet the FM one at about 60 dB below the maximum average power of the FM unit. In a similar extrapolation, if an ACSSB unit using an extra linear power amplifier was used, and its 70 dB bandwidth was restricted to that of the baseband bandwidth (i.e., about 3 kHz), this value would be about 65 dB below the maximum power of the FM. Hence, using very narrow bandwidth technologies, it looks like their interstitial insertion between two existing FM stations would yield levels of interference

(on the FM) close to the ones produced by the adjacent FM stations, therefore causing relatively little additional degradation to the existing FM systems in the VHF band.

3.1.6 Discussion

Although not introduced as an important parameter in the calculation of the spectrum efficiency, the 70 dB bandwidth, representing the level of interference on the adjacent channel, becomes a factor that has to be considered when one wants to introduce new systems in the VHF band. Since, in order to obtain the same kind of performances in terms of interference level and dynamic range for co-located adjacent stations, the channel spacing of the new systems should also be based on their 70 dB bandwidth. Otherwise, as will be shown in section 3.5, the interference from the adjacent stations becomes too high, and at the limit, adjacent station frequencies can not be used in the same cell, thereby greatly reducing the spectrum efficiency.

Appearing severe at first hand, a 70 dB rule for establishing the channel spacing is not unreasonable, considering that much stricter rules have been suggested by International Committees such as the CCIR (International Radio Consultative Committee): for example [133], for 25 and 30 kHz channel spacing, the CCIR recommends that the adjacent channel power should be *at least 70 dB below carrier power in a bandwidth of 16 kHz*, for 20 kHz channel spacing, *at least 70 dB below carrier power in a bandwidth of 14 kHz*, and for 12.5 kHz channel spacing, *at least 60 dB below carrier power in a bandwidth of 8.5 kHz*.

Although the only Radio Standard Specification available for SSB radios (RSS-125) does not cover the frequency band of the tested units, it is the one suggested by the Canadian Department of Communication to be used for SSB above 30 MHz. It was shown that both the SSB and the ACSSB units meet the minimum spurious emissions performance standard specified in the RSS-125, and therefore could fit into the 3 kHz channel spacing allocated in the HF band. Since these units could be allocated a 3 kHz channel spacing in the HF band, one wonders why a 5 kHz channel spacing can not be used in the VHF band. The answer is partly provided by the fact that the existing FM systems in the VHF band have a 70 dB bandwidth long-time voice emitted spectra, whereas the one required in HF is about 40 dB. Any new technology introduced in the VHF band will also have to respect this 70 dB criteria, otherwise, its presence in this band will result in higher adjacent channel level of interference on the existing FM. Hence, the co-existence of the old and new technology in this case impose such a restriction.

On the other hand, if no system already existed in a frequency band would it be reasonable to reduce this limitation, for example to 40 dB. Channel spacing based on the 40 dB bandwidth has been suggested in the past as a base for future system design. The ACSSB and SSB systems could then be allocated a 5 kHz channel spacing. As mentioned, one would necessarily have to suffer a degradation in terms of the dynamic range for co-located adjacent stations. But what about the effect of the increased interference imposed on the receivers of the adjacent channel frequencies? Hence, a comparison of the emitted spectrum, and the tentative channel spacing values obtained from it are not sufficient by themselves to answer these question nor the other questions asked at the beginning of this study. For example, in order to calculate the spectrum efficiency of the various systems, the co-channel separation distances must be taken into consideration. To do so, protection ratios at various frequency separations are required. Also, protection ratio values will add parameters that are needed in a more accurate determination of the channel spacing, since the emitted spectrum alone does not yield any indication about the resistance of the receiver to interference. Also, the results of interference levels between the ACSSB and the FM systems will enable one to determine the effects, on the FM stations, of inserting interstitial ACSSB channels, and will yield indications of how an eventual replacement of some FM stations by ACSSB ones in this band will influence the remaining FM systems. This is done in section 3.3, as part of a general interference study between the systems.

RES BW 30 Hz
VBW 30 Hz
SWP 20 sec
CENTER 145.00188 MHz
SPAN 10.00 kHz

ICOM-SSB
NO MODULATION
MAX HOLD FOR 2 MINUTES

FIGURE 3.20 : ICOM-SSB transmitted spectrum, No Modulation

RES BW 30 Hz
VBW 30 Hz
SWP 20 sec
CENTER 146.00188 MHz
SPAN 10.00 kHz

ICOM-SSB; PEP=10 Watts
MOD=SINGLE 1 KHZ TONE
MAX HOLD FOR 2 MINUTES

FIGURE 3.21 : ICOM-SSB Tx Spectrum, 1 kHz Tone, 10 Watts PEP

RES BW 30 Hz
VBW 30 Hz
SWP 50 sec
CENTER 145.00000 MHz
SPAN 20.00 kHz

ICOM-SSB; Mod=2 equal Tones.
850 and 1950 Hz; PEP = 10 W.
MAX HOLD for 4 SCANS

FIGURE 3.22 : ICOM-SSB Tx Spectrum, 2 Tones, 10 Watts PEP

RES BW 100 Hz
VBW 100 Hz
SWP 5.0 sec
CENTER 145.00000 MHz
SPAN 20.00 kHz

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ICOM-SSB; MOD=2 NE TONES
12 dB DIFF.; PEP=10 W.
MAX HOLD for 2 MINUTES

FIGURE 3.23 : ICOM-SSB, 2 Not Equal Tones; 10 Watts PEP

FIGURE 3.24 : STI-ACSSB 1 kHz and ICOM-SSB/norm. 2 NE tones

RES BW 100 Hz
VBW 100 Hz
SWP 5.0 sec
CENTER 145.00000 MHz
SPAN 20.00 kHz

ICOM-SSB; MAX PEP = 10 W.
VOICE MODULATION
MAX HOLD for 3 MINUTES

FIGURE 3.25 : ICOM-SSB Tx Spectrum, Voice, 10 Watts PEP

FIGURE 3.26 : ICOM-SSB Tx spectrum: Voice, 2 NE Tones, and Noise

FIGURE 3.27 : STI-ACSSB and ICOM-SSB/normalized, Voice

FIGURE 3.28 : ICOM-SSB Tx spectrum, Voice - 5 kHz Channels

FIGURE 3.29 : STI-ACSSB and MCX-FM, Long Time Voice

FIGURE 3.20 : 2 STI-ACSSB and 2 MCX-FM, Long Time Voice

3.2 SENSITIVITY EVALUATION

When one wants to compare the various modulation schemes, for example, in an interference and protection ratio study, it becomes essential to have a uniform evaluation criteria that can be used equivalently on the various tested systems. In this section, the transmission properties of the tested systems will be examined, and a SINAD evaluation measurement procedure will be established for the 3 schemes under test.

3.2.1 SINAD Measurement Procedure for Each Scheme

3.2.1.1 GENERAL METHOD OF MEASUREMENT

Generally, the measurement technique consists of applying an RF signal of known amplitude and modulating frequency (usually 1 kHz audio tone) to the antenna input of the receiver. The audio power output (over the audio bandwidth of the receiver) is then measured; this power consists of the total sum of the recovered modulation, the distortion products produced by the receiver non-linearities, and the amplified thermal noise of the signal source and receiver. A narrow band rejection filter, tuned to the modulating frequency, is then interposed between the receiver audio output and the power meter. A second power reading is obtained which now is due to the distortion plus noise output. The ratio of the first power to the second, expressed in decibel, is called the dB SINAD for the given signal level and modulation.

3.2.1.2 FM SYSTEMS

SINAD sensitivity for an FM system is usually defined as the minimum level of standard modulated RF input signal at the receiver's resonant frequency which will produce a SINAD of 12 dB, with at least 50 % of the rated audio output power (e.g., RSS-119). The standard modulated RF input signal is normally obtained from an FM signal generator, modulated with a 1000 Hz signal, and adjusted to a level that will produce a frequency deviation of 60 % of the system peak modulation deviation (i.e., 3 kHz, for the 5 kHz frequency deviation FM system used in this study). It is known that the relative carrier and side-frequency amplitudes in an FM signal vary with the amplitude and frequency of the modulating signal, but that the total power contained in the RF modulated waveform remains constant. Thus, the 12 dB SINAD level is obtained using the total (average or peak envelope) power contained in the RF modulated waveform, and not the level (power) of the carrier or any particular frequency components.

3.2.1.3 SSB SYSTEMS

In contrast to FM, the SSB modulated waveform average power is directly proportional to the level of the modulating signal. Consequently, the 12 dB SINAD level is dependent on the power of the modulated RF signal.

The modulating signal level is not limited by a modulation index as in the case of FM or AM. The limitation is imposed by the Peak Envelope Power (PEP) that the transmitter can develop without introducing additional distortion to the modulating signal. This is usually set as the Rated PEP for the transmitter. If the amplitude of the modulating signal exceeds the level that produces rated PEP, limiters (clippers) in the audio input line will be enabled and will restrain the amplitude of the signal, introducing at the same time distortion to it. Generally, if the amplitude of the modulating signal is reduced, the RF output power will be proportionally reduced.

Thus, for SINAD measurements, the amplitude of the 1 kHz modulating signal would have to be adjusted to produce the maximum power without introducing additional distortion, i.e., it must be adjusted to produce rated PEP. If the modulating signal was set lower than this limit, the average power and the 12 dB SINAD level would be reduced accordingly.

The SINAD measurement is made simple for SSB because, when the unit is modulated with a single audio tone, the RF modulated waveform consists of a single RF tone. In this case the Peak Envelope Power (PEP) and the average power are the same. The level of this single RF tone is simply attenuated until the 12 dB SINAD is obtained. The single RF tone is usually provided by a signal generator.

Thus, as for the FM systems, the 12 dB SINAD level is obtained using the total (peak envelope or average) power contained in the modulated waveform. For SSB, this level is also the level of a single RF frequency component.

3.2.1.4 ACSSB SYSTEMS

For the same reasons as the ones mentioned above for SSB, the level of the modulating signal in an ACSSB transmitter must be adjusted to produce rated PEP at the output of the transmitter, and the 12 dB SINAD will be obtained by attenuating this RF modulated signal.

Looking back at the STI-ACSSB 1 kHz modulated emitted spectrum (figure 3.12), one sees that for SINAD measurements, two RF tones need to be applied to the antenna

input of an ACSSB receiver in order to obtain a single tone audio output signal. One RF tone must represent the pilot frequency and the other, the 1 kHz audio signal.

The relative power difference (Δ in dB) between the RF pilot frequency and the RF 1 kHz frequency must also be maintained since it represents the conditions obtained when the unit is transmitting at rated PEP.

In this case, a problem concerning the various ways of expressing the power of this RF signal now appears since, in contrast to FM and SSB SINAD measurements, the average and Peak Envelope power of a two tone signal are not the same.

Looking at figure 3.9, one sees that the PEP is a measure of the maximum attainable average power, and represents the power of the peak envelope voltage. Therefore, the PEP effectively represents the true average power only a very small fraction of the time. On the other hand, the short-time (instantaneous) average power varies with time. But for FM and SSB, the average power (which was constant) was used to determine the SINAD level; consequently, the long-time average power would be the appropriate value for ACSSB. With a periodic signal such as the two tone signal, the long-time average power can be calculated or measured (figure 3.9-E and Appendix C). Hence, the level (power) of the ACSSB modulated waveform at which the 12 dB SINAD is obtained should be given in terms of the long-time average power of the modulated waveform.

3.2.2 Experimental Evaluation

3.2.2.1 FM

The 12 dB SINAD of the three FM systems under test in this study was measured using the measurement method described above (which in fact corresponds to the one usually given in FM radio standard specification, e.g., RSS-119), and was found to be respectively: -118.5 dBm (.266 μ V) for the MCX-FM unit, -119.5 dBm (.237 μ V) for the FORCE-FM, and -121.5 dBm (.188 μ V) for the ICOM FM unit.

In terms of 20 dB quieting, the levels obtained were -116.5 dBm (.335 μ V) for the MCX FM unit, -118.5 dBm (.266 μ V) for the FORCE-FM one, and -120.5 dBm (.211 μ V) for the ICOM FM.

One notes that for the FM systems, the single RF tone used for the quieting measurement effectively represents an FM signal with no modulation (i.e., carrier only). One

can also see that the values of the 20 dB quieting and SINAD are relatively similar for FM systems.

3.2.2.2 SSB

The 12 dB SINAD for the ICOM-SSB was obtained using the measurement method described above for SSB and is also the same as the one given in the radio standard RSS 125. The 12 dB SINAD was found to be -124.5 dBm (.133 μ V).

Unfortunately, the 20 dB quieting for the SSB is impossible to obtain, since a single RF tone that falls into the RF bandwidth of an SSB unit will translate into an audio tone (when the single RF tone is tuned to the assigned frequency, it represents a 1.4 kHz modulated tone).

3.2.2.3 ACSSB

The SINAD for the STI-ACSSB was also measured following the method described above. For simplicity of measurement, the long-time average power of the signal was calculated from the highest component (i.e., the RF 1 kHz tone) of the two RF frequency signal, using the method described in Appendix C. For 12 dB SINAD, the level of the 1 kHz RF tone was found to be -110 dBm. Since the RF pilot tone is 12 dB below this level, the long time average power (thus the 12 dB SINAD) is -109.73 dBm (.729 μ V). Note that the PEP is 1.9 dB above this value. Considering the measurement precision, and the small difference in average power between the 1 kHz RF tone (-110 dBm) and the long time average power (-109.73 dBm), the level of the 1 kHz RF tone can then be considered as approximately equal to the long-time average power, and could be used for SINAD measurements on the ACSSB units.

The 20 dB quieting for the STI-ACSSB units was found to be of -120 dBm (.224 μ V). Note that in this case, the receiver locks on the single RF tone used for this measurement, and it interprets the received signal as the RF pilot tone. This has the effect of dropping the audio noise level to its minimum, since there is no audio modulation on the RF waveform. This explains the fact that the 20 dB quieting is much lower than the SINAD value.

3.2.3 Discussion

There has been some controversy in the past regarding the RF power (average or PEP) and component (pilot tone or 1 kHz) that should be used to represent the SINAD of the ACSSB systems. But as seen, the long-time average power of the complete modulated signal should be used for such measure.

In general, considering the modulation schemes under test, one can conclude that the 20 dB quieting method is not a comparative figure representative of the receiver selectivity of various modulation systems; although the values obtained for the FM systems are relatively close to the SINAD values, it differ by as much as 10 dB for the ACSSB system. Moreover, the 20 dB quieting measurement is not always possible to obtain, as was seen for SSB.

Also, from this comparison, one could conclude that in general, for various modulation schemes, the level used for the 12 dB SINAD measurements should be given in terms of the long-time average power of the RF modulated signal used to make the measurement.

3.3 INTERFERENCE MEASUREMENTS

In this section, objective and subjective measurements similar to the ones that have generally been used in the past in various interference studies, or that are being currently used by some radio standards, are done on the systems under test. The problem with the multiplicity of available testing methods is that an interference study done on one system, using a given method, will yield results different from one done with another method. The comparison incompatibility increases when different methods are used for testing different systems. It is hoped, by comparing the results obtained using these different techniques, to find one that yields the most useful information on the susceptibility of the systems to interference, and to suggest it as a unified method in future measurements. A generally accepted method would make possible, in the future, comparative analysis of different systems tested by different groups.

Because a subjective evaluation is related directly to the intelligibility of the tested system, it appears at first that it would be the most interesting candidate. But subjective measurements involve the need for human listening, and sometimes yield results that can be dependent on the observers. These problems are eliminated when an objective measure is used, and this is highly desirable. Comparing the various available techniques is therefore a first step in the search of an objective method that will yield results similar to a subjective one.

But the major objective of this section is also directly related to the main goal of this study, the comparison of the spectrum efficiencies of FM, ACSSB, and SSB. As seen, the determination of the interference rejection of these systems is essential in order to assign a channel spacing in the VHF for the new technologies, and in order to obtain the parameters needed for spectrum efficiency calculations (i.e., re-use distance). If a representative method of evaluation is found, a better spectrum efficiency comparison of the various modulation schemes will be possible. Moreover, the results of interference between the ACSSB and the FM systems will enable us to find if, as suggested, ACSSB channels can be inserted between adjacent FM channels, and will give us an indication of how an eventual replacement of some FM stations by ACSSB ones in this band would influence the remaining FM systems.

3.3.1 Test Set-Up

The general test set-up used for the measurements described in this study is shown in figure 3.31. Variations and improvements to this basic test set-up were made for some measurements, and are described as encountered.

The emissions at the output of the transmitters were needed in order to accurately evaluate the protection ratios of the different systems (this is discussed in more detail in section 3.4.3). Because of the high signal levels involved when 25 to 35 Watts transmitters are used, the two transmitters and the receiver were installed in individual shielded enclosures, providing a total of about 200 dB⁴ isolation between the transmitter output and the receiver input. At the very beginning of the experiment, single braid coaxial cables were used to interconnect the various elements of this test set-up, but it was soon found that leakage through these cables was high enough to falsify the results, specially when the high power transmitted signals were greatly attenuated. Single braid coaxial cables provide very poor RF shielding (at 150 Mhz, the total power radiated by one foot of cable is about 50 dB down from the signal level in the cable [134]; this value is increased to about 80 dB for double braid coaxial), and the use of semi-rigid solid sheath cables was considered as compulsory to carry all the RF signals. Semi-rigid solid sheath cables provide an adequate isolation of more than 250 dB [134].

Except for the RF lines, the external connections to and from the shielded enclosures (e.g., DC power supply, input/output audio lines, etc.) were made through at least two independently shielded high isolation RF filters.

For subjective measurements, the voice modulation for the desired and undesired transmissions was supplied by 2 pre-recorded tapes, containing news passages read by male speakers. In order to easily differentiate between the desired and interfering signal, the 2 tapes contained different (independent) voice passages. Each audio line was DC isolated and the impedances were matched.

⁴ Considering a 35 watts transmitter (45.4 dBm), and a receiver that can detect a signal as low as -130 dBm, one works with a range of 175 dB.

Shielded enclosures usually provide between 70 to 120 dB isolation, depending on the type of their construction. Our set-up used double-shielded, common ground type shielded enclosures, which provides about 100 dB isolation (per shielded enclosure). With the double shield isolated (no common ground between the two shield) this type of enclosure would provide about 120 dB isolation.

Depending on the required output RF level, a power attenuator of 20 or 40 dB was used and installed in the shielded enclosure at the output of the transmitter. A variable attenuator was installed on each RF line, and the two signals were combined with an RF combiner. This combined RF signal was then directly feed into the receiver input. The desired signal level was monitored at the output of the combiner. The variable attenuators were used to set the various levels of desired and undesired signal.

The audio output of the receiver was fed into headphones, speakers, or audio recorder for subjective evaluation purpose, or into the SINAD meter for objective measurements.

This whole set-up was eventually automated (for the objective measurements) using GP-IB programmable instruments (attenuators, audio analyser, frequency generators, etc.) and an HP 85 laboratory computer/controller. The protection ratio data was first stored in the HP 85 computer, then transferred to the mainframe to be plotted. The data was passed through a least squares cubic spline smoothing routine before being plotted.

3.3.2 Calibration Procedure

3.3.2.1 FREQUENCY

The local oscillator frequency of the interfering transmitter was varied so that its assigned frequency was adjusted to obtain the required frequency separation. A sample of the transmitted frequency was monitored on a frequency counter and the assigned frequency adjusted or calculated as described below.

For FM transmissions, the carrier frequency of the RF unmodulated waveform (when no modulation was applied to the input of the transmitter) was used, and yielded directly the assigned frequency.

For ACSSB, the RF pilot frequency (pilot only transmission as presented before) was used, and the assigned frequency calculated from this value.

For SSB, the transmitter was modulated with a 1 kHz audio tone, the frequency of the RF 1 kHz tone measured, and the assigned frequency calculated from this value.

Occasionally, the frequencies of the on-channel transmitter and receiver also had to be adjusted. In this case, both on-channel transceivers were operated in the transmitter mode and their frequencies adjusted accordingly.

At the beginning of the measurements, the potentiometer of the local oscillator circuit of the transceivers was varied to obtain the various assigned frequencies. But this led to a lengthy task:

- because of the relatively poor long term stability of the transceiver's oscillators, a readjustment of all the units was done for each set of measurements.
- the interfering frequency required for the frequency separation under test had to be manually adjusted for each measurement.
- because of the limited range of this adjustment, only a limited number of interfering frequencies were available.

As a sufficient number of signal generators could be gathered, the frequency provided by the local oscillator of the transceiver was replaced with one provided by the signal generator. This set-up has the advantage of having more flexibility and of providing a more stable local oscillator frequency. Finally, if programmable signal generators are used, all the local oscillator frequencies can be adjusted and varied under computer control, greatly simplifying this frequency adjustment task.

3.3.2.2 SIGNAL LEVEL

The transmitted signal level at the output of the combiner was measured on the spectrum analyser. The signal was modulated as described below.

1) FM Signal

Since the envelope of an FM signal has a constant amplitude, the power of the RF waveform remains constant and is the same when there is no modulation, or when the unit is modulated with a single (1 kHz) audio tone, or when it is voice modulated. The level of the FM transmitted signal at the output of the combiner was hence determined by measuring, on the spectrum analyser, the level of the (single RF tone) carrier, when no modulation was applied to the input of the transmitter, with the variable attenuator set to zero. The desired or undesired level was then simply calculated from this level by adding the amount of attenuation provided by the variable attenuator.

The level of the modulating signal at the input of the FM transmitter was adjusted so that it would not exceed a pre-determined deviation.

2) SSB Signal

In contrast to FM, the total average power on an SSB modulated waveform is not constant, but varies as a function of the amplitude of the modulating signal. On the other hand, the PEP is fixed and remains constant, independent of the modulating signal. When the transmitter is modulated with a single audio tone, a single RF tone is present at the output and the PEP is equal to the average power level as read on a spectrum analyser.

When the SSB system is voice modulated, the average power will vary, but the PEP remains fixed. The average power will be lower than it was when the unit was modulated with a single audio tone, but the PEP will remain the same.

Although some authors have used in the past short-term mean power to defined voice modulated SSB RF power, this definition leads to a signal level which is from 6 to 10 dB lower than the power that must actually be supplied by the transmitter during the voice modulation peaks, and mean power is now considered irrelevant for protection ratio comparisons [135]. Consequently, reference to voice modulated RF power in SSB (and ACSSB) is usually given in terms of Peak Envelope Power.

For voice, the level of the modulating signal at the input of the SSB transmitter was adjusted so that it would not exceed rated PEP. This was done by connecting a Peak Envelope meter directly at the output of the SSB transmitter. The PEP level was determined using the single RF tone produced when the SSB transmitter is modulated with a 1 kHz audio tone. This signal was measured (on the spectrum analyser) at the output of the combiner (with the variable attenuator set to zero), and the level of the desired or undesired signal simply calculated from this PEP level by adding the amount of attenuation provided by the variable attenuator. Since the PEP is the same for voice and single audio tone modulation, this value is consequently representative of the PEP of these two modulating signals.

3) ACSSB Signal

Because the ACSSB transceivers tested in this study have an internal push-button which, when activated, transmits only the RF pilot tone at rated PEP level, the PEP reference signal level was determined as described above for SSB.

In the case of a 1 kHz audio tone modulating signal adjusted to produce rated PEP, a different procedure was sometimes used: as seen, with the STI-ACSSB units, the PEP is, in these units, 1.9 dB above the average power level of the 1 kHz RF tone. Thus, the level

of the 1 kHz RF tone was read on the spectrum analyser and the PEP given by adding 1.9 dB to this value.

3.3.3 FM into FM Interference Objective Measurements

3.3.3.1 12 TO 6 DB SINAD SINGLE RF TONE PROTECTION RATIOS

1) The test

This test measures the ability of the FM receiver to process an on channel desired signal, without exceeding a specified degradation of the audio output, in the presence of a single (unmodulated) RF tone interfering at different frequencies around the assigned frequency. The on-channel signal was provided by a signal generator modulated with a 1 kHz audio tone, with its level adjusted so that the deviation was 4.5 kHz. This RF signal was then attenuated to obtain 12 dB SINAD on the receiver's audio output (RF level of -118.5 dBm for the MCX-FM unit). The interfering (unmodulated) single RF tone was also provided by a signal generator, its frequency was tuned to the frequency separation under test, and its amplitude was increased until the 12 dB SINAD (of the demodulated desired signal) degraded to 6 dB SINAD (averaged over 10 samples).⁵ The ratio in dB between the two signal levels at the receiver antenna input is the *12 to 6 dB SINAD single RF tone Protection Ratio*, the reference (0 dB) being the 12 dB SINAD level (e.g., -118.5 for the MCX-FM unit).

This test is similar to the spurious response immunity test of the EIA Radio Standard RS-204-C [116] (used in the U.S. for FM land mobile equipment). It represents the protection ratios obtained with the minimum possible interference (a single RF tone) on the FM stations.

2) Results for the 3 FM units

Figure 3.32 shows the results obtained for the 3 FM units. One can see that the ICOM-FM unit has the best (narrowest) single RF tone protection ratio in the interstitial channel region (± 15 kHz), and that the Force unit has the worst one (widest curve). One also observes that, around the assigned frequency, an interfering signal of lower power than the desired signal power produces the interference, an indication that the on channel region is highly sensitive to interference.

⁵ This was all done under computer control.

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It can be seen that an interfering station with the smallest possible bandwidth (i.e., a single RF tone interfering), inserted at the interstitial channel (15 kHz), degrades, for some FM systems, the protection ratio by at least 15 dB, compared with the one obtained at the adjacent channel (30 kHz): For the MCX-FM and FORCE-FM, at the interstitial frequency, a single RF tone interfering signal 60 dB stronger than the one of the desired channel produced a 12 to 6 dB SINAD degradation. At the adjacent channel frequency, the degradation was produced with an interfering signal 75 dB stronger or more. Since such a narrow interstitial channel causes some disturbance, it can already be concluded that, unless the receiver of these VHF FM systems are made using sharper input filters, no co-located station, no matter how small in bandwidth, can be inserted at the interstitial frequency, without producing to the on-channel station a degradation slightly worse than the one produced by an adjacent station.

3.3.3.2 TWO SIGNAL SELECTIVITY 12 TO 6 DB SINAD PROTECTION RATIOS

1) The Test

In this test, both the interfering signal and the on-channel signal are modulated. The on-channel signal is provided by a signal generator, and the modulating signal is either a 400 Hz or a 1 kHz audio tone. Its amplitude is adjusted to produce either 3 or 4.5 kHz deviation. The RF level of this signal is decreased until the 12 dB SINAD is obtained. The interfering signal is also provided by a signal generator, modulated with a 1 kHz audio tone, and adjusted to produce either 3 or 4.5 kHz FM deviation. Its RF frequency is then tuned to the frequency separation under test, and its level is increased until the 12 dB SINAD degrades to 6 dB SINAD (averaged over 10 samples). The difference in dB between the levels of the desired (on-channel) and of the interfering (undesired) signal at the receiver antenna input terminal is called the *two signal selectivity 12 to 6 dB SINAD Protection Ratio*, and the reference (0 dB) is the on-channel signal level that produced the 12 dB SINAD.

Actually, this test was done following the "Two Signal Selectivity and Desensitization Characteristic" described in the RSS-119. Some of the parameters (i.e., frequency deviation and frequency of the modulating tone) were varied to see their effect on the protection ratio curve. This test is also relatively similar to the adjacent channel selectivity test of the RS-204-C, but in this case a 15 to 12 dB degradation is used.

2) The MCX Unit

The two signal selectivity protection ratios, measured with various parameters, for the MCX-FM unit are shown in figure 3.33. This figure contains four curves and the parameters for each curve is described in Table 2. Curve 1 was done using the parameters of the RSS-119 (i.e., on-channel modulation of 1 kHz at 3 kHz frequency deviation, interfering signal with a modulation of 400 Hz at 3 kHz deviation). Curve 2 is similar, except that a 1 kHz audio tone was used instead of a 400 Hz one for the interfering signal. One can see from this figure that the effect of using a 1 kHz tone instead of the 400 Hz tone has practically no effect on the two signal selectivity protection ratios. This is not surprising, since, it could be seen (on a spectrum analyser) that the RF power spectrum produced using a 1 kHz or a 400 Hz modulating tone (both adjusted to produce a deviation a 3 kHz) have a similar bandwidth.

A comparison of curves 3 and 4 show that a change in the frequency deviation of the on channel signal (from 3 to 4.5 kHz) also produces very little difference in the protection ratio curve.

Curves 2 and 3 show the effect of increasing the frequency deviation of the interfering signal. As the frequency deviation is increased, the bandwidth used by the interfering signal increases (see figures 3.2 and 3.3), and a wider protection ratio curve results. A difference of up to 6 dB in the protection ratios can be noticed at some points. This fact can also be inferred when comparing the single RF tone interference protection ratio curve (figure 3.32) with this one. One could also intuitively have deduced that, as the interfering channel bandwidth is increased, the protection ratio curves get wider, showing that the on-channel signal is more disturbed by larger bandwidth interfering channel.

Curve #	Desired Signal		Interfering Signal	
	Audio Modulation	Frequency Deviation	Audio Modulation	Frequency Deviation
1	1 kHz	3 kHz	400 Hz	3 kHz
2	1 kHz	3 kHz	1 kHz	3 kHz
3	1 kHz	3 kHz	1 kHz	4.5 kHz
4	1 kHz	4.5 kHz	1 kHz	4.5 kHz

TABLE-2: MCX-FM System, Two Signal Selectivity Variations

3) FORCE-FM and ICOM-FM units

The two signal selectivity 12 to 6 dB SINAD protection ratios measured using the parameters given in the RSS-119 were also obtained for the two other FM units: the FORCE FM, and the ICOM-FM. The results for these two units, along with the one of the MCX unit (from figure 3.33) are shown in figure 3.34. One can see again the better performances of the ICOM-FM receiver over the two other systems.

A two signal selectivity protection ratio of -70 dB at adjacent channels (± 30 kHz) is given as the minimum performance standard in the RSS-119. One sees that these FM units comply well to this standard. Actually, this minimum performance is respected up to ± 20 kHz. Using only this criteria, and referring to figure 3.34, one would be tempted to conclude that the channel spacing could be reduced from 30 kHz to 20 kHz, without further significant degradation on the desired station. But, as will be shown later, this does not hold for voice modulation. In passing, the minimum adjacent channel selectivity recommended by the CCIR [133] is also 70 dB, for channel spacings of 20, 25, and 30 kHz, although in this case, the test procedure and the interference criteria used are not well defined.

No RSS-119 performance standard is given for the on-channel frequencies, but instead, it specifies a minimum of 16 dB between the two signal selectivity values of the on-channel and of the interstitial frequencies. From figure 3.34, one sees that for the 3 tested units, there is more than 40 dB between the values of these two frequencies.

In summary, for the RSS-119 two signal selectivity measure, the protection ratios for the 3 tested FM units were about 5 to 9 dB at the on-channel frequency, and about -34 to -58 at the interstitial frequency. At 20 kHz, the protection ratios were smaller than -70 dB, and at 30 kHz, smaller than -75 dB.

FIGURE 3.32 : Single RF Tone interference Protection Ratios of 3 FM

FIGURE 3.33 : MCX-FM, Two Signal Selectivity Protection Ratios

FIGURE 3.34 : Two Signal Selectivity Protection Ratios of 3 FM

3.3.4 FM into FM Subjective Interference Measurements

3.3.4.1 THE SUBJECTIVE TEST

In the disruptive and just noticeable subjective tests, both the on-channel and interfering transmitters are modulated with voice. Hence, this situation represents the real life situation of two co-located transmitters both used for voice communications. Their only separation is per the given frequency separation. The on-channel transmitted signal level is adjusted to the "desired signal level" and is coupled to the on-channel receiver input. The frequency of the interfering transmitter is adjusted as per the "frequency separation" under test, and its level is varied until it produces, at the audio output of the on-channel receiver, either the just noticeable or the disruptive interference. The level at which the interference criteria is met is recorded, and the protection ratio is the ratio of the undesired to desired signal (at the input of the receiver). The reference (0 dB) is taken as the level of the on-channel signal. This test is repeated for various on-channel signal levels, and various frequency separations.

For FM, the voice modulation level (provided by the tape recorders) at the microphone input of each transmitter was adjusted as to obtain a maximum (peak) frequency deviation of 4.5 kHz at the output of the transmitters.

Because of the long-term involvement required for this series of measurement, only two listeners were used to obtain the subjective protection ratios of this study. The results presented are the average values obtained. It has been shown in the past (e.g., [136]) that the level at which disruptive interference is detected does not usually vary too much from one listener to another. On the other hand, the level at which the just noticeable interference is detected can vary more, as a function of the listener, as a function of the amount of noise already present in the transmission, and as a function of the ambient noise of the room where the trial is conducted. Therefore, the results obtained in this study can be considered as representative for the disruptive measurements. A variation of less than 4 dB between the results of the two listeners was observed in our case. The variation was larger for the just noticeable case. To compensate for this deficiency, the fact that the just noticeable interference is more detectable when there is no modulating signal at the input of the on-channel transmitter was used. This condition occurs when the user transmits but does not talk (silence periods). The protection ratio at which this condition was measured is called the

just noticeable interference with no on-channel modulation, and is abbreviated by *J-N-N-M*, *Just Not. N.M.*, or *Just Noticeable N.M.*

Because very weak RF signal levels introduce more noise in the demodulated audio of the received signal, it becomes more difficult to evaluate the just noticeable interference as the noise level increases (i.e., as the on-channel RF signal level decreases). Consequently the just noticeable tests were done for relatively strong levels of the on-channel transmitted signal (i.e., -60 dBm, and -90 dBm).

3.3.4.2 SUBJECTIVE INTERFERENCE FOR THE MCX-FM UNIT

This test was done with the MCX-FM unit for various levels of the on-channel transmitted signal: -60 dBm, -90 dBm, -110 dBm, and -118.5 dBm. Curves 1 to 4 of figure 3.35 show the protection ratios required to avoid disruptive interference with these 4 different on-channel signal levels. One realizes that these protection ratio curves are wider (i.e., worse) than the previous objective ones. One also notices that there is no major variations in the protection ratios when the on-channel signal level is varied.

Note that in this test, the -118.5 dBm on-channel (voice modulated) signal level is at the same power level as the one that was required to obtain the 12 dB SINAD sensitivity level of the receiver (one should not confuse the fact that the on-channel signal is modulated with a 1 kHz tone for the 12 dB SINAD but with voice for the subjective evaluation). Since the level of the on-channel signal does not affect noticeably the protection ratios, the curve obtained at this power level will be used, in the comparative figures between the various units, as the one representing the subjective interference protection ratio curve.

The protection ratios required by the MCX unit to avoid just noticeable (Just Not.) and just noticeable with no on-channel modulation (J-N-N-M) interference are also displayed in figure 3.35.

One can see from these results that the just noticeable interference is detected with an interfering signal about 25 dB lower than the level required to produce disruptive interference, but that the general shape of the protection ratio curve is very similar to the disruptive one. As a result, the disruptive interference protection ratio curve could be raised by about 25 dB, and this would approximate the just noticeable interference one.

As expected, the just noticeable with no on-channel modulation interference requires lower interfering signal levels than those of the just noticeable case, but this requirement is accentuated close to the center frequency; the difference is smaller in the sloped regions.

3.3.4.3 SUMMARIZING THE DIFFERENT KINDS OF INTERFERENCE FOR THE MCX FM UNIT

Four major criteria for evaluating interference have been dealt with so far: the single RF tone, the two signal selectivity as described in the RSS-119, the disruptive interference, and the just noticeable interference. The effect of the various interference criteria on the protection ratios can be better seen when these 4 curves are regrouped together. This was done for the MCX-FM unit, and is shown in figure 3.36.

One sees that the effect of increasing the interfering channel bandwidth from a single RF tone, to a 1 kHz tone at 3 kHz deviation (see figure 3.2), and to a voice signal with a peak frequency deviation of 4.5 kHz (see figure 3.4), results in a widening of the protection ratio curves. This could have been deduced intuitively. Around the assigned frequency, the variation in the protection ratios of the 3 lower curves is relatively small, less than 5 dB. But, as will be seen in the following sub-section, a few dB difference in the protection ratio of the assigned frequency yields a large difference in the interfering distance of the co channel stations, thus, playing a very important role in the calculation of the re use distance, and consequently, on the calculation of the spectrum efficiency. In a similar way, the difference in the protection ratios at the adjacent channel frequency plays a role in the establishment of the minimum geographical distance that 2 adjacent stations should have.

Naturally, one also observes a very large difference, for all frequency separations, in the protection ratios obtained with an interference criteria such as the just noticeable criteria compared to the protection ratios obtained with the disruptive interference one.

More generally, the modulation level of the interfering signal (i.e., the interfering signal bandwidth), as well as the interference criteria used, both play a very important role in the value of the protection ratios obtained for various frequency separations. It is therefore already evident that comparing protection ratios obtained from various studies, where different interference criteria and different interfering signals were used, can only yield incommensurable results.

FIGURE 3.35 : MCX-FM, Subjective Interference Comparison

FIGURE 3.36 : Comparison of Various Interference Criteria, MCX-FM

3.3.4.4 INTERFERING DISTANCES OF THE MCX-FM INTO MCX-FM INTERFERENCE

For the MCX unit, the highest protection ratio values (considering all the curves of the same type in figure 3.35, and positive as well as negative frequency separations) that produced disruptive and just noticeable interference are summarized in Table 3; the two signal selectivity protection ratio curve (measured as per RSS-119) was also added as a means of comparison. The given values in the table can be considered as the worst case values, since they represent the highest protection ratio values obtained at these frequency separations and would require the largest geographical separations when the interfering signal is produced by a transmitter.

One sees that for this unit, a voice modulated adjacent channel (30 kHz away), can have a power level of up to 74 dB above the on-channel signal level before it starts to produce disruptive interference on the latter. This value goes down to 44 dB to avoid any kind of just noticeable interference. An interstitial channel that is about at the same power level as the desired one will produce just noticeable interference, but if it is about 25 dB stronger, it will produce disruptive interference. For the co-channel situation, an interfering station that is 7 dB lower in power than the level of the desired station will produce disruptive interference.

For the worst case values given in Table 3, the interfering distances, calculated using the propagation model described in section 2.3.4, are shown in Table 4, and illustrated in figure 3.37. One can see that generally, the differences in the calculated interfering distances resulting from these various interference criteria are also very large.

For all frequency separations, there is a major difference in the interfering distances between the disruptive and just noticeable cases. One sees that to avoid any kind of interference, co channel bases stations would have to be put very far away from each other, and the re-use distance for identical assigned frequencies would be extremely large. A geographical separation distance of the order of 70-75 miles is currently suggested in the Canadian frequency allocation scheme [128] as the re-use distance between co-channel base stations. Since this is also the interfering distance obtained with the model used here, a re-use distance of the order of 400 miles would be required for an interference-free environment (i.e., for users to notice absolutely no interference from the co-channel stations, J-N-N-M case). Although this calculated re-use distance is unrealistic, and even if it was 2 or 3 times smaller, an interference-free environment is unthinkable because of the adverse impact it would have on efficient frequency usage.

Accordingly, one can conclude that, because the subjective disruptive interference gives a measure of the limit of intelligible operation of the system, this criteria (and not the just noticeable ones) is the one that yields the most critical information for the protection ratio measurements in the land mobile environment context. The user can get his message across up to the disruptive interference level of degradation.

3.3.4.5 DISRUPTIVE INTERFERENCE AND INTERFERING DISTANCES OF THE 3 FM UNITS

Some of the results of the disruptive interference measurement obtained for the 3 FM units are compared in figure 3.38, and the highest protection ratio levels for the various frequency separations are given in Table 5. One can see again the better performances of the ICOM FM unit over the two others.

Note that a set of measurements similar to the one shown in figure 3.35 was done for both the FORCE-FM and the ICOM-FM. The same conclusions as the ones reached for the MCX-FM were confirmed with these measurements, i.e, there was no major variations in the protection ratios when the on-channel signal level was varied, and the just noticeable interference curves were between 15 to 25 dB above the disruptive ones. Since no additional information was provided by these curves, they were not included here. Only the disruptive interference protection ratio curves taken at the same power level as the 12 dB SINAD level were used in figure 3.38. On the other hand, the highest protection ratio values of Table 5 were extracted from the series of curves, and the values used here for the MCX FM are the same as the ones of Table 3.

It can be seen that by using 3 different FM systems of the same type, the interference rejection of the FM receivers from different manufacturers are different. But the difference was not expected to be so large: one observes (Table 5), in the sloped regions of these disruptive protection ratio curves, a difference of as much as 13 dB between the MCX and the FORCE units, and of as much as 23 dB between the MCX and the ICOM FM ones. On the other hand, in the co-channel region, the protection ratios are practically the same for the 3 units, but they are found to be varying from -74 to -82 dB for the adjacent channel frequency, and from -19 to -34 for the interstitial one.

The results of testing only 3 different FM receivers of the same type show that, in any experimental interference evaluation, the protection ratios obtained can only apply to the specific tested units. Except for the co-channel frequencies, generalizing the results obtained

with only one system can be misleading. Referring back to the review of protection ratio, done by Crombie (mentioned in the introduction of this study), one can conclude that just the differences between the (FM) tested equipment of the same nominal type might contribute a lot to the incommensurability of the protection ratio measurements. In other words, interference protection ratio measurements done with different FM systems show different results, and this is accentuated outside the on-channel region. Note that this conclusion applies to both the objective and subjective measures.

For the values given in Table 5, the interfering distances, calculated as described in section 2.3.4, are illustrated in figure 3.39 and shown in Table 6. The differences between the three transceivers, around the co-channel frequency, is very high, of the order of 20 miles. At the offset (interstitial) channel, the FORCE-FM units would have to be separated by about 17 miles to avoid disruptive interference, but the ICOM units could be half this distance. At 12.5 kHz both the MCX and the ICOM units require geographical separation of the order of 22 to 24 miles; 50 miles is required for the FORCE. The Canadian frequency allocation scheme suggests a geographical separation distance for interstitial channel (15 kHz offset) of the order of 25-35 miles. For the adjacent channel stations, a geographical separation of about 1 mile is suggested, when no special protection is provided. For this case, our model yields a disruptive interfering distance in the range of .5 to .7 miles.

Re-use distance (often calculated using exclusively the co-channel interference protection ratio) is one of the important parameters used in the calculation of spectrum efficiency. Looking at the disruptive co-channel protection ratio values of the 3 FM (Table 5), one realizes that they are effectively about the same for the 3 systems. But a difference of about 20 miles in the re-use distance calculations of these 3 FM systems is obtained when using those protection ratios.

This shows the important effect of the receiver's sensitivity on the effective re-use distance that is computed using the protection ratios. In spectrum efficiency evaluation, the calculation of the re-use distance is most of the time exclusively based on the (on-channel) protection ratios, without taken into account the sensitivity of the receiver. This is a serious deficiency, because, as shown above, the extent of the denied area is also a function of the sensitivity of the receiver under consideration.

Frequency Separation (kHz)	MCX-FM into MCX-FM Highest Protection ratio (dB)			
	Disruptive Interference	Just Noticeable Interference	Just Not. N-M Interference	Two Signal Selectivity
35	-82	-59	-55	-88
30	-74	-50	-44	-86
25	-66	-45	-38	-83
20	-50	-28	-23	-69
17.5	-36	-15	-12	-59
15	-25	-3	2	-41
12.5	-13	10	13	-23
10	-5	19	23	-5
7.5	2	25	32	6
5	6	30	37	6
2.5	7	30	37	7
0 (co-channel)	7	29	37	7

TABLE-3: Highest Protection Ratios of MCX-FM into MCX-FM

Frequency Separation (kHz)	MCX-FM into MCX-FM Worst Interfering Distances (miles)			
	Disruptive Interference	Just Noticeable Interference	Just Not. N-M Interference	Two Signal Selectivity
35	0.42	1.58	1.99	.30
30	0.67	2.66	3.75	.33
25	1.06	3.54	5.30	.40
20	2.66	9.43	12.57	.89
17.5	5.95	19.92	23.68	1.58
15	11.20	39.75	53.01	4.46
12.5	22.35	84.02	99.85	12.57
10	35.43	141.05	177.57	35.43
7.5	53.01	199.24	298.10	66.74
5	66.74	265.68	397.53	66.74
2.5	70.69	265.68	397.53	70.69
0 (co-channel)	70.69	250.82	397.53	70.69

TABLE-4: Worst Interfering Distances of MCX-FM into MCX-FM

Frequency Separation (kHz)	FM into FM Highest Protection ratio (dB)		
	MCX Disruptive	FORCE Disruptive	ICOM-FM Disruptive
35	-82	-76	-83
30	-74	-75	-82
25	-66	-73	-82
20	-50	-60	-73
17.5	-36	-42	-55
15	-25	-19	-34
12.5	-13	0	-15
10	-5	5	-4
7.5	2	6	2
5	6	6	5
2.5	7	7	7
0 (co-channel)	7	8	8

TABLE-5: Highest Disruptive Protection Ratios of the 3 FM Systems

Frequency Separation (kHz)	FM into FM Worst Interfering distances (miles)		
	MCX Disrup. Interference	FORCE Disrup. Interference	ICOM Disrup. Interference
35	0.42	0.63	0.47
30	0.67	0.67	0.50
25	1.06	0.75	0.50
20	2.66	1.58	0.84
17.5	5.95	4.46	2.37
15	11.20	16.76	7.93
12.5	22.45	50.05	23.68
10	35.13	66.74	44.60
7.5	53.61	70.69	63.00
5	66.74	70.69	74.88
2.5	70.69	74.88	84.02
0 (co-channel)	70.69	79.32	89.00

TABLE-6: Worst Disruptive Interfering Distances of FM into FM

Tx=25 Watts, 50 feet, Rx=-118.5 dBm, 50 feet, F=150 Mhz

FIGURE 3.37 : Interfering distance for MCX-FM into MCX-FM

FIGURE 3.38 : Disruptive Interfer. Protection Ratios, 3 FM units

Tx=25 Watts, 50 feet, Rx=-118.5 to -121.5 dBm, 50 feet, F=150 MHz

FIGURE 3.39 : Disruptive Interfering distance for the 3 FM units

3.3.5 ACSSB into ACSSB Interference Measurements

3.3.5.1 OBJECTIVE MEASURES: SINGLE RF TONE AND TWO SIGNAL SELECTIVITY

For the single RF tone receiver selectivity, the on-channel signal was provided by an STI transmitter, modulated with a 1 kHz audio tone, and adjusted to produce 25 Watts PEP. It was then attenuated to obtain a 12 dB SINAD on the audio output of the receiver. The interfering single RF tone was provided by a signal generator, its frequency adjusted to the measured frequency separation, and its level increased until the 12 dB SINAD degraded to 6 dB SINAD (averaged over 10 values). The two signal selectivity test is similar, except that the interfering signal was provided by another STI transmitter modulated with a 1 kHz audio tone adjusted to produced 25 Watts PEP. The protection ratio curves obtained for these 2 tests are shown in figure 3.40. Curve 1 shows the 12 to 6 dB SINAD protection ratio obtained when the interfering signal is a single RF tone, and curve 2 when the interfering signal is a 1 kHz modulated ACSSB signal.

Note that as for FM, a larger bandwidth interfering signal has the effect of widening the protection ratio curve in the sloped regions. Because of the receiver design differences related to a much narrower bandwidth, the width of the ACSSB protection ratio curves is much smaller than that of FM. As for FM, a co-channel interfering signal a few dB lower (in power) than the desired signal produces the degradation in the receiver audio output.

The method of measurement used to obtained the above single RF tone protection ratio curve is very similar to the two signal selectivity measure described in the SSB radio standard (the RSS-125). The minimum performance standard in this case requires that the protection ratio be smaller than -60 dB at ± 2.6 kHz of the assigned frequency. From figure 3.40, one sees that the ACSSB unit meets this requirement.

3.3.5.2 SUBJECTIVE PROTECTION RATIOS AND INTERFERING DISTANCES OF ACSSB INTO ACSSB

This test is similar to the subjective tests done on the FM units; recall that for subjective evaluation, the desired and undesired channels are both modulated with voice. Some tests were repeated for different RF levels of the on-channel transmitted signal: -60 dBm, -90 dBm, and/or -110 dBm. Note that the -110 dBm voice modulated RF level is at the same power level as the one that yielded the 12 dB SINAD sensitivity for this unit (where the

modulation was a 1 kHz tone). The level of the modulating signal at the microphone input of each transmitter was adjusted as to obtain a maximum PEP of 25 watts at the output of the transmitters.

Figure 3.41 shows the STI into STI subjective protection ratio curves. One notes that, as for the FM protection ratio curves, a variation of the level of the desired signal (i.e., the C/N ratio of the desired signal) has not too much effect on the protection ratios, and similar protection ratio curves are obtained for the various on-channel signal levels.

Recall that for FM the just noticeable interference protection ratio curve could be obtained from the disruptive curve by raising the latter by about 20-25 dB. In the case of ACSSB the variation between the two set of curves is not as uniform: for the just noticeable interference, the difference is about 20 dB at the extremities of the curves, but it goes down to about 10 dB in the sloped regions, and to about 7 dB at the co-channel location. For the just noticeable N-M, it is about 25 dB at the extremities, and about 15-20 in the sloped regions and at the co-channel location.

The highest protection ratios required to produce disruptive, just noticeable and just noticeable N.M. interference for this ACSSB unit are summarized in Table 7:

Comparing these critical protection ratios with the ones obtained for the FM units (Table 3 and Table 5), one could reach a few conclusions:

- For FM, the highest disruptive protection ratio found for the adjacent channel situation was of -74 dB. If the same level of protection is sought for the STI ACSSB units, the adjacent channel would need to be a bit more than 10 kHz away (-71 dB for 10 kHz - Table 7)
- If the just noticeable criterion was used, the relative interfering signal level for the MCX-FM is 50 dB at 30 kHz; it is 49 dB at 7.5 kHz for the STI ACSSB unit, leading to a possible channel spacing of 7.5 kHz.
- Finally, if the single RF tone interference is used (figure 3.32), the FORCE FM unit shows a protection ratio of about -75 dB at 30 kHz, leading to a possible channel spacing of about 4 kHz for the STI-ACSSB unit (figure 3.40).

As can be seen, the multiplicity of interference criteria leads to various results, in this case to various suggested channel spacing. But, as for the case of FM into FM interference, it is reasonable to use for ACSSB the disruptive interference criteria since, as explained before, it is the most representative one in the land mobile environment. Using this criteria, and

assuming that an adjacent channel protection ratio for ACSSB similar to the ones obtained in this situation for FM is wanted, a channel spacing of about 10 kHz for protection ratio of the order of -70 dB is required for ACSSB. The choice of -70 dB for FM is based on the highest value found for the worst FM system (-74 dB) with allowance for slightly worse receiver design that could be found if a larger number of FM systems had been tested. Note also that at -70 dB protection, the FORCE and the ICOM could support respectively about a 25 kHz and a 20 kHz channel spacing (see Table 5).

For the highest protection ratios of ACSSB into ACSSB, the interfering distances calculated as described previously are illustrated in figure 3.42, and shown in Table 8.

Most of the time, the average power is used in the calculations done with propagation models. The long term average power of the STI peaks at about 10 watts when the unit is voice modulated. The maximum short term power is, at the limit, the PEP. So by using the PEP as the power value in the propagation model, the interfering distances are really the worst possible ones, since the model assumes that the ACSSB always transmits at an average power of 25 watts, while it does so extremely rarely.

Using the same propagation loss equation, the calculated interfering distances of the STI ACSSB into STI-ACSSB are much lower than the one obtained for FM into FM; This is not surprising, since the 12 dB SINAD sensitivity of the ACSSB unit is much higher (i.e., worse) than those of the FM systems. As seen for FM, the sensitivity of the receiver plays an important role in the calculation of the interfering distances. In this case, this leads to a smaller re-use distance for the ACSSB system (39 miles for ACSSB compared to 70 to 89 for FM), which can be advantageous in an interference environment. Naturally, the higher 12 dB SINAD sensitivity of the ACSSB system also yields a smaller coverage area, and this can be disadvantageous; this subject will be discussed in more detail in chapter 4. This higher sensitivity of the ACSSB system can also explain why some studies have found the coverage area of ACSSB to be smaller than that of FM.

Note also that the margin between the disruptive and the just noticeable interference cases is smaller for the STI. This is considered advantageous, since an "interference-free" criteria would be easier to apply with the ACSSB systems than with the FM ones.

At adjacent channel spacing (30 kHz), the lowest disruptive interfering distance calculated with our model was of 0.5 mile for FM. The 0.5 mile disruptive interfering distance for ACSSB is obtained with a frequency separation of 10 kHz. Using our model, one notes

that a geographical separation of about 3.5 miles is required for 2 adjacent ACSSB with a 5 kHz channel spacing.

Note that, contrary to FM in the VHF band, no guideline is provided by the Canadian Department of Communications regarding suggested geographical separation distances for co-located, interstitial, or adjacent channel SSB stations in the HF. The frequency allocation in this band is done on a case by case basis. Moreover, protection from harmful sky wave interference is an additional problem in this band that is not present in the VHF and UHF bands. Therefore, a comparison with the frequency allocation scheme for HF is not possible here.

3.3.5.3 SUMMARY OF THE DIFFERENT KINDS OF INTERFERENCE FOR THE ST1 ACSSB UNITS

Four protection ratio curves obtained using different desired and undesired modulation, and different interference criteria are shown for comparison purposes in figure 3.43. The figure displays the disruptive and the just noticeable interference protection ratio curves, alongside the single RF tone and the two signal selectivity ones.

One notes that for ACSSB, the two signal selectivity protection ratio curve is similar to the disruptive interference curve. This can be explained by the fact that the ACSSB emitted spectrum modulated by a 1 kHz tone covers approximately the same bandwidth as the long-time voice emitted spectrum (see figure 3.19).

In the case of FM, the two signal selectivity curve is obtained with an interfering signal modulated with a 400 Hz at 3 kHz frequency deviation. The emitted spectrum of this modulation is much smaller than the one obtained for the long time voice, and the two signal selectivity protection ratio curve is consequently narrower than the disruptive interference one (see figure 3.36).

In the past, the two signal selectivity curves have been sometimes used as a means of comparing the protection ratios of FM and ACSSB. As seen above, this comparison is not valid since the two signal selectivity curve is almost equal to the disruptive interference one for ACSSB but is not for FM.

Frequency Separation (kHz)	STI-ACSSB Worst Protection ratio (dB)		
	Disruptive Interference	Just Noticeable Interference	Just Not. N-M Interference
20	-86	-69	-63
15	-82	-62	-59
12.5	-78	-60	-55
10	-71	-53	-50
7.5	-59	-49	-46
5	-37	-28	-18
2.5	-4	5	17
0 (co-channel)	5	9	19

TABLE-7: Highest Subjective Protection Ratios of the STI-ACSSB System

Frequency Separation (kHz)	STI into STI Worst Interfering distances (miles)		
	Disruptive Interference	Just Noticeable Interference	Just Not. N-M Interference
20	.21	.55	.77
15	.26	.82	.97
12.5	.32	.92	1.22
10	.49	1.37	1.63
7.5	.97	1.73	2.05
5	3.44	5.78	10.28
2.5	23.01	38.62	77.07
0 (co-channel)	38.62	48.63	86.47

TABLE-8: Worst Interfering Distances of STI-ACSSB into STI-ACSSB

FIGURE 3.40 : STI-ACSSB, Single RF tone and 2 Signal Selectivity

FIGURE 3.41 : STI-ACSSB into STI, Subjective Interfer. Comparison

$T_x=25$ Watts, 50 feet, $R_x=-110$ dBm, 50 feet, $F=150$ Mhz

FIGURE 3.42 : Interfering Distances for STI-ACSSB into STI-ACSSB

FIGURE 3.43 : STI-ACSSB Comparison of Various Interferences

3.3.6 FM into ACSSB Interference Measurements

A similar set of measurements was done to obtain the protection ratios of FM interfering into ACSSB. As the emitted spectrum of the 3 tested FM systems are very similar (figure 3.7), only one series of measurement was done with the MCX-FM interfering into the STI-ACSSB system.

Figure 3.44 shows the STI-ACSSB protection ratio curves required to avoid disruptive, just noticeable and just noticeable N-M interference, with the on-channel signal being set at different RF levels, when the MCX-FM is interfering into this ACSSB system. As for the previous sets of subjective protection ratio curves, one can conclude that a variation of the on-channel signal level does not seriously affect the curves, and that the just noticeable situations in this case could be deducted by raising the disruptive curve by about 15 dB.

Because of the wide emitted spectrum of the FM transmission, these protection ratio curves are located about midway between the subjective ACSSB into ACSSB and the FM into FM ones.

The highest protection ratios required to produce disruptive, just noticeable and just noticeable N-M interference on the STI-ACSSB unit are summarized in Table 9. For these values, the interfering distances calculated as described before are illustrated in figure 3.45 and shown in Table 10.

Naturally, because of the larger emitted spectrum of the FM, the interfering distance as a function of the frequency separation decreases more slowly than in the case of an ACSSB interfering.

One also notes that the STI unit is less affected by a co-channel FM interfering signal than it was by a co-channel ACSSB one. This is shown by the lower protection ratio and smaller disruptive interference distance of this situation compared to the ACSSB into ACSSB one.

Using our model, it can be seen from the 15 kHz interfering distance that an ACSSB unit inserted at the interstitial frequency of two adjacent FM stations would resist strongly the interference produced by the FM stations. It would actually need a very small geographical separation to avoid disruptive interference caused by the FM stations. It was seen before that, using this model, two adjacent FM stations require a geographical separation of between .5 to .67 miles to avoid disruptive interference. Adjacent FM with an interstitial ACSSB station would require the ACSSB to be separated by .69 miles to avoid disruptive

interference from the FM stations. Since co-located adjacent FM stations are assigned in the VHF (with geographical separation of the order of 1 miles [128]), it is concluded that, from the ACSSB point of view, an interstitial ACSSB, between 2 FM, would be relatively viable, in the context of the present frequency allocation scheme.

On the other hand, if two ACSSB, 5 kHz between them, are inserted between adjacent FM stations, not only would they require geographical separation between each other, but they would also require a larger than 0.7 mile geographical separation from the FM stations. For example, with this model, 2 ACSSB, 5 kHz apart, require a geographical separation of about 3.5 miles to avoid disruptive interference caused by each other. If these 2 stations were inserted midway between 2 adjacent FM ones, the frequency separation between one ACSSB and one FM is 12.5 kHz (figure 3.30). To avoid disruptive interference from the FM, the ACSSB should be geographically separated from the FM by about 1.5 miles.

Frequency Separation (kHz)	STI-ACSSB Highest Protection ratio (dB)		
	Disruptive Interference	Just Noticeable Interference	Just Not. N-M Interference
25	-84	-71	-67
20	-78	-63	-58
15	-65	-50	-45
12.5	-52	-33	-28
10	-37	-17	-14
7.5	-22	-2	-2
5	-10	4	6
2.5	-2	8	14
0 (co-channel)	2	14	17

TABLE-9: Highest Subjective Protection Ratios of MCX-FM into STI-ACSSB

Frequency Separation (kHz)	MCX into STI Worst Interfering distances (miles)		
	Disruptive Interference	Just Noticeable Interference	Just Not. N-M Interference
25	.23	.49	.61
20	.32	.77	1.03
15	.69	1.63	2.17
12.5	1.45	4.33	5.78
10	3.44	10.89	12.94
7.5	8.16	25.81	25.81
5	16.29	36.46	40.91
2.5	25.81	45.91	64.84
0 (co-channel)	32.50	64.84	77.07

TABLE-10: Worst Interfering Distances of MCX-FM into STI-ACSSB

FIGURE 3.44 : MCX-FM into STI-ACSSB Subjective Interf. Comparison

Tx=25 Watts, 50 feet, Rx=-110 dBm, 50 feet, F=150 Mhz

FIGURE 3.45 : Interfering distance for MCX-FM into STI-ACSSB

3.3.7 ACSSB into FM Interference Measurements

Finally, a last set of similar measurements was done to obtain the protection ratios of the STI-ACSSB unit interfering into the MCX-FM system. As the characteristic of the receivers of the three FM systems under test are different, disruptive protection ratios of ACSSB interfering into the FORCE-FM and the ICOM-FM links were also obtained.

Figure 3.46 shows the STI-ACSSB into the MCX-FM protection ratios required to avoid disruptive, just noticeable and just noticeable N.M. interference, with the on-channel signal being set at different RF levels.

Naturally, because of the narrower emitted spectrum of the ACSSB, the protection ratio curves are narrower than in the FM into FM case, but, because of the wider IF filters of the FM receivers, FM systems are more affected by interference from ACSSB than ACSSB was by FM. Also, the same conclusions mentioned before regarding the various levels of the on-channel signal, and the just noticeable interferences are also confirmed with this case: as for the other subjective measurements, variation of the on-channel signal level does not influence noticeably the protection ratio curves; similar to the FM into FM measures, the just noticeable protection ratio curve is about 20 dB higher than the disruptive one, and the just noticeable with no on-channel modulation curve is higher than the just noticeable one outside the sloped regions.

Also, as in the case of FM into ACSSB, the FM units are less affected by a co-channel ACSSB interfering station than it was by a co-channel FM one. Therefore, both the FM and the ACSSB systems are more resistant to co-channel interference from foreign modulation schemes than from their own.

Subjective disruptive protection ratios of the STI into the 3 FM units are compared in figure 3.47, and the highest protection ratios are shown in Table 11. One can see again that the ICOM unit has the narrowest protection ratio curve.

As for FM into FM, note that a set of measurements similar to the one shown in figure 3.46 was done for both the FORCE-FM and the ICOM-FM. Since no additional information was provided by these curves, they were not included here. Only the disruptive interference protection ratio curves taken at the same power level as the 12 dB SINAD level were used in figure 3.47. On the other hand, the highest protection ratio values of Table 11 were extracted from the series of curves.

From the results shown in figure 3.47 and Table 11, the protection ratios that would be obtained if a hypothetically smaller emitted spectrum ACSSB signal was used can be extrapolated. Consider, for example, a 5 kHz (70 dB bandwidth) ACSSB signal as the interfering signal. This would be, in terms of level of interference, about equivalent to the actual 10 kHz ACSSB located 17.5 kHz from the FM one. It is seen that at this frequency separation, the protection ratios for the 3 FM systems are from -63 to -77 dB. Therefore, one can conclude that in general VHF FM systems would still suffer from the insertion of smaller bandwidth interstitial channels, but the degradation could be considered acceptable. Consequently, the possibility of inserting narrowband technologies between existing VHF FM stations seems to be possible, as long as the interstitial station has a 70 dB bandwidth emitted spectrum equal to or smaller than 5 kHz.

For the highest protection ratios of ACSSB interfering into FM systems, the subjective interfering distances calculated as described previously are shown in figure 3.48 and in Table 12. The interfering distance values show that an STI-ACSSB inserted at the interstitial frequency (15 kHz) of two FM would require a compulsory geographical separation (from about 1.3 to 3 miles using this model) from the FM units to avoid causing disruptive interference to the FM. Hence, the FM is more affected by the interstitial presence of the ACSSB than the ACSSB was of the FM. On the other hand, if the ACSSB was located 20 kHz away, more normal co-location geographical separation would be required.

The co-channel interference-free criteria (just noticeable interferences) separation distance for ACSSB into FM (figure 3.48) is similar to the FM into FM case (figure 3.37). As seen, an interference-free criteria applied to FM into ACSSB (figure 3.45) and to ACSSB into ACSSB (figure 3.42) would require much smaller geographical separation.

3.3.8 Comparison of Some Interference Results between FM and ACSSB

Using some of the protection ratio curves of the preceding sections, a comparison of the disruptive interference between one ACSSB and one FM system can be done. The four disruptive interference combinations: FM into FM, FM into ACSSB, ACSSB into ACSSB, and ACSSB into FM are shown in figure 3.49. The parameters of the curves used in this figure are given in Table 13.

For these protection ratio values, the interfering distances have been calculated before and were shown in the preceding figures and tables. They were regrouped in figure 3.50 for ease of comparison.

It is easier to see now what has been mentioned before: the ACSSB is less influenced by interference from FM than FM is by ACSSB. Because of the wide IF filter of the FM receiver, it is much more open to interference than is ACSSB.

Although these curves yield a comparative figure, one should not generalize too much from these two last figures; as shown before, these curves represent the situation only for the specific units tested. As seen, for example in figures 3.38 and 3.47, the range of the protection ratios is quite large when more than a single system is tested for each modulation scheme. The range of interfering distances for a given frequency separation in this case was also, as seen, very large.

Frequency Separation (kHz)	STI-ACSSB into 3 FM: Highest Protection Ratios (dB)		
	STI into MCX Disruptive	STI into Force Disruptive	STI into ICOM Disruptive
30	—	—	-85
25	-77	-78	-82
20	-71	-71	-80
17.5	-63	-66	-77
15	-48	-55	-65
12.5	-32	-38	-45
10	-15	-15	-21
7.5	-2	-1	-6
5	1	0	-2
0 (co-channel)	-2	-1	0

TABLE-11: Highest Disruptive Protection Ratios of STI-ACSSB into the 3 FM Systems

Frequency Separation (kHz)	STI into 3 FM Worst Interfering distances (miles)		
	STI into MCX Disruptive	STI into Force Disruptive	STI into ICOM Disruptive
30	—	—	.42
25	.56	.63	.50
20	.79	.84	.56
15	2.98	2.11	1.33
12.5	7.49	5.62	4.21
10	19.92	21.10	16.76
7.5	42.11	47.25	39.75
5	50.05	50.05	50.05
0 (co-channel)	42.11	47.25	56.15

TABLE-12: Worst Disruptive Interfering Distances of STI-ACSSB into the 3 FM Systems

Curve #	Desired Signal: System, Modulation	Desired Signal Level (PEP or average Power)	Interfering Signal: System, Modulation	Interference Criteria: Subjective
1	STI-ACSSB, Voice	-110 dBm	STI-ACSSB, Voice	Disruptive
2	STI-ACSSB, Voice	-110 dBm	MCX-FM, Voice	Disruptive
3	MCX-FM, Voice	-118.5 dBm	STI-ACSSB, Voice	Disruptive
4	MCX-FM, Voice	-118.5 dBm	MCX-FM, Voice	Disruptive

TABLE-13: Comparison of Disruptive Protection Ratios: MCX-FM and STI-ACSSB Systems

FIGURE 3.46 : STI-ACSSB into MCX-FM Subjective Interf. Comparison

FIGURE 3.47 : STI-ACSSB into FM Disruptive Interfer. Comparison

Tx=25 Watts, 50 ft, Rx=-118.5 to -121.5 dBm, 50 f., F=150 Mhz

FIGURE 3.48 : Interfering distance for STI-ACSSB into the 3 FM

FIGURE 3.49 : Disruptive Interfer. between FM and ACSSB Systems

Tx=25 Watts, 50 feet, Rx=-110 or -118.5 dBm, 50 feet, F=150 Mhz

FIGURE 3.50 : Disruptive Interfering distances between FM and ACSSB

3.3.9 SSB Interference Measurements

In order to complete the comparison between the modulation schemes tested in this study, a few interference measures using the ICOM-SSB unit were done.

A two signal selectivity measure similar to the one described in the RSS-125 is compared to the disruptive interference in figure 3.51. The interfering single RF tone was provided by a signal generator. The disruptive interference was measured with the voice modulated on-channel signal level set at the same level as the one required for the 12 dB SINAD sensitivity, i.e., -124.5 dBm. Note that the SSB units meet the two signal selectivity minimum performance standard (-60 dB at ± 2.6 kHz of the assigned frequency) of the RSS-125.

Note also on this figure a 12 to 6 dB SINAD degradation curve taken with the interfering signal provided by the transmitter modulated with a 1 kHz tone. One sees that the protection ratios in the case where the interfering signal is provided by the transmitter are slightly worse than in the case where it was provided by the signal generator; this is explained by the fact that the emitted spectrum of the transmitter in this case (see figure 3.21) has a few spurious frequencies, and a noise level higher than the ideal single RF tone provided by a signal generator. This difference between protection ratio values obtained using a signal generator compared to the ones obtained using the transmitter for the interfering signal will be discussed in more detail in section 3.4.

Contrary to the ACSSB into ACSSB case, the subjective disruptive protection ratio curve of SSB into SSB is much wider than the two signal selectivity one. This is explained by the fact that there is no pilot in the SSB case, and that the 1 kHz modulating tone produces a single RF tone when modulated. In the ACSSB case, the resulting interfering signal was a two tone signal that produced intermodulation in the power amplifier section.

Using the -70 dB disruptive protection ratio criteria found for adjacent channel FM, one sees that this level is obtained in this case for channel spacing of about 9 kHz.

The SSB into SSB disruptive interference protection ratio curve is compared in figure 3.52 with a disruptive ACSSB into ACSSB one (from figure 3.41). The 2 protection ratio curves (curves 1 and 2) are similar in shape, except that the protection ratios of the SSB receiver are better, close to the assigned frequency. In the same figure, the disruptive protection ratios curves of ICOM-SSB into MCX-FM and STI-ACSSB into MCX-FM (from figure 3.46) are also compared. The curves (3 and 4) again have a similar shape, but one notices

that the ICOM-SSB has a less severe influence than the STI-ACSSB on the MCX-FM; this is probably due to the wider ACSSB emitted spectrum compared to the SSB one.

Finally, the disruptive interference protection ratio curve of MCX-FM into SSB along with the MCX-FM into ACSSB (from figure 3.44) are shown in figure 3.53. The curves have a very similar shape, except that the SSB unit seems to be slightly less resistant to FM interference than the ACSSB unit is about the co-channel frequency.

The highest disruptive protection ratios for SSB and FM interference are shown in Table 14. Using our propagation model, the worst case disruptive interfering distances are displayed in figure 3.54, and shown in Table 15. When comparing these values with the ones obtained for the MCX-FM and ACSSB cases, one sees that the co-channel disruptive interference protection ratio for FM was 7 to 8 dB, for ACSSB, it was 5 dB, and for SSB it is -1 dB; the disruptive interfering distances were from 70 to 89 miles for FM, 39 miles for ACSSB, and is 63 miles for SSB. The lower required co-channel protection ratio for SSB might be attributed to the fact that SSB does not have a capture effect. One notes that the co-channel interfering distance of the SSB is noticeably higher than the one for ACSSB, although it is shown that, at that frequency, the protection ratio of the SSB is lower than the one of the ACSSB. This again can be explained by the much higher (worse) 12 dB SINAD sensitivity of the ACSSB receiver compared to the SSB one. This also explains the much higher interfering distances required to avoid disruptive interference from the FM unit. Finally, the disruptive interfering distances of ACSSB into FM are a bit larger than the SSB into FM ones; as explained before, this can be caused by the wider emitted spectrum of ACSSB compared with the SSB one.

Frequency Separation (kHz)	Highest Disruptive Protection Ratios (dB)		
	ICOM-SSB into ICOM-SSB	ICOM-SSB into MCX-FM	MCX-FM into ICOM-SSB
30	-97	-87	-81
25	-96	-85	-78
20	-94	-82	-76
17.5	-92	-75	-73
15	-90	-65	-65
12.5	-84	-50	-51
10	-76	-28	-37
7.5	-65	-10	-20
5	-52	-2	-3
2.5	-21	-4	5
0 (co-channel)	-1	-5	3

TABLE-14: Highest Disruptive Protection Ratios: SSB and FM Systems

Frequency Separation (kHz)	Worst Interfering Distances (miles)		
	ICOM-SSB into ICOM-SSB	ICOM-SSB into MCX-FM	MCX-FM into ICOM-SSB
30	0.25	0.32	0.63
25	0.27	0.35	0.75
20	0.30	0.42	0.84
17.5	0.33	0.63	1.00
15	0.38	1.12	1.58
12.5	0.53	2.66	3.54
10	0.84	9.43	7.93
7.5	1.58	26.57	21.10
5	3.34	42.11	56.15
2.5	19.20	37.53	89.00
0 (co-channel)	63.00	35.43	79.32

TABLE-15: Worst Disruptive Interfering Distances: SSB and FM Systems

FIGURE 3.51 : ICOM-SSB into ICOM-SSB Protection Ratios

FIGURE 3.52 : Disruptive Interference of SSB, ACSSB, and FM

FIGURE 3.53 : Disruptive Interfer. of MCX-FM into SSB and ACSSB

Tx=25 Watts, 50 feet, Rx=-110 dBm, 50 feet, F=150 Mhz

FIGURE 3.54 : Interfering Distances for ICOM-SSB and MCX-FM

3.4 A SUBJECTIVELY EQUIVALENT OBJECTIVE MEASUREMENT METHOD

In this section, a comparison is done between the objective and subjective criteria used in section 3.3. Using information gathered throughout this study, an objective criteria that produces protection ratios similar to the ones obtained with the subjective disruptive criteria is derived, and suggested as a unified measurement method.

3.4.1 Towards an Equivalent Subjective and Objective Method

A repeatable, automated, and relatively precise objective method of measuring the protection ratios that would yield values similar to the one obtained with the disruptive interference criteria is desired. As we have seen, the disruptive interference criteria is the one that yields the most useful information for the land mobile environment. Subjective evaluation of disruptive interference is tedious and time consuming, involving listeners. If one has to do it for many transceivers, it becomes an excessively long task. In order to facilitate future interference measurements, a relation between subjective and objective measurements was sought.

In a first trial, the subjective disruptive protection ratio curve of the MCX -FM was compared with its two signal selectivity (12 to 6 dB SINAD) results obtained with various frequency deviation of the interfering signal. A comparison of the curves obtained was shown in figures 3.36 and 3.33. Recall that in the two signal selectivity case, the on channel and the interfering modulating signals were modulated with a 1 kHz audio tone. From figure 3.36, one can see that the general shape of the subjective disruptive curve differs from the shape obtained with the two signal selectivity one. When the frequency deviation of the interfering signal is increased in the two signal selectivity measure, the width of the protection ratio curve increases, but its general shape stays the same, and does not follow the shape of the disruptive interference case.

This difference in the shape of the curves can be explained by two differences in the measurement parameters: first, signal generators are used for the two signal selectivity measure while a transmitter is used for the disruptive one; second, the spectrum of the interfering signal is different: in one case the interfering signal is modulated with voice, and in the other case with a 1 kHz tone.

One then concludes that using a 1 kHz tone modulating signal for the undesired signal can not produce protection ratio curves similar to the subjective disruptive case.

On the other hand, it has been shown before that the level and frequency of the modulating signal of the desired station has little effect on the protection ratio curves. For example, that an on-channel signal modulated with a 1 kHz tone or with voice produced similar results. This could also have been intuitively concluded by realizing that the receiver is open to all signals that fall inside its bandwidth, and that similar interference will be caused to whatever the desired signal is. Recall that, in the case of the disruptive interference measurement, the undesired transmitted signal was modulated with voice, and that the voice amplitude at the microphone input of the transmitter was adjusted to obtain a maximum frequency deviation of 4.5 kHz at the output of the transmitter. It then seems logical, in the search to find an objective measurement that yields results similar to the subjective measure, to use a 1 kHz audio tone as the on-channel modulating signal, and to interfere with a voice modulated one. That way, one can measure the SINAD degradation of the on-channel signal, while the interfering signal is the same as it was in the subjective evaluation measurements.

Two levels of SINAD degradation have been suggested in the past as representing the passage from acceptable to unacceptable signal degradation (i.e., equivalent to disruptive degradation): the 12 to 6 dB SINAD, and the 15 to 12 dB SINAD. In both cases, a 1 kHz tone is required as the desired (on-channel) signal. The level of the 15 dB SINAD for FM is usually 1.5 to 2 dB higher than the value of the 12 dB SINAD. For the MCX-FM unit it was measured and found to be -117 dBm.

The testing method of this objective measure can be then described as follow: the objective interference protection ratio is the ratio (in dB) of the interfering signal level to the desired signal level present at the receiver input that will result in a degradation of the SINAD at the receiver output from 12 to 6 dB (or from 15 to 12). In this case, the desired signal is modulated with a 1 kHz tone, and its RF level is the 12 (or 15) dB SINAD level; the undesired (interfering) signal is modulated with voice, and its RF level is varied until the objective criteria (12 to 6 dB SINAD or 15 to 12 dB SINAD) is met. A number of tests were done using this method.

In figure 3.55, the protection ratios obtained using this method and the ones obtained with the subjective disruptive interference measurement are compared. The subjective disruptive measure is the same as the one displayed in figure 3.35, with the on-channel voice

modulated signal level at -118.5 dBm. The 12 to 6 dB SINAD and the 15 to 12 dB SINAD measures were done as described above. Also, a 12 to 6 dB SINAD measure was obtained with a noise generator, instead of the voice, as the modulation of the interfering signal. This last curve will be discussed below.

One can see that the 12 to 6 dB SINAD objective measure done with voice modulation on the interfering channel corresponds closely to the subjective disruptive interference situation, but that although the 15 to 12 dB SINAD protection ratios are similar to the subjective results in the sloped regions, they differ by as much as 10 dB around the assigned frequency.

The same similarities were observed when this objective method was used with the various systems tested in this study. Figure 3.56 shows the comparison for the STI-ACSSB into STI-ACSSB case, figure 3.57 for the STI-ACSSB into MCX-FM interference, figure 3.58 for the MCX-FM into STI-ACSSB case, and figure 3.59 for the STI-ACSSB into the ICOM-FM case. It can be seen from these figures that the 15 to 12 dB SINAD method does not yield results that are similar enough to the subjective disruptive interference case to be considered as adequate, but that the 12 to 6 dB SINAD method does.

Measurements on these units consequently lead to the following conclusion: When compared using the same interfering (undesired) signal (i.e., voice), the subjective disruptive interference protection ratios are similar to the ones obtained using a 12 to 6 dB SINAD objective measure.

3.4.2 The Audio Noise Generator as the Interfering Modulation

Because the voice signal varies constantly in amplitude and frequency, it produces a large variation of the emitted spectrum when it is modulated. A consequence of having the interfering channel voice-modulated is that it produces a variation in the level of the interference detected on the desired channel. In the subjective measurement, the disruptive interference occurs most of the time when the voice peaks. In the above objective measurement, the 6 dB SINAD level is not stable and it oscillates around its value. With some systems, when the voice peaks, the 6 dB is obtained, but when the voice modulation is low or non-existent, the SINAD tends to go back towards the 12 dB value. An average of some limited quantity of SINAD samples then varies slightly, depending on the amount of talking during the sampling time. This was solved in our case by increasing the length of sampling, but it led to longer waiting period for the operator.

Also, it is sometimes argued that the speakers used for the modulating voice signal in subjective measures vary from one study to the other, perhaps contributing to some difference in the results obtained. If a generalized method of measurement is to be established, the modulating signal used in the various studies must be the same.

It was found that by using an audio noise generator as the modulating signal for the interfering signal, these problems were solved, and that generally, it would lead to more repeatable protection ratio measurements. An audio noise generator with a spectral response that simulates the long term power density spectrum for continuous speech [137] was used in this study. A more detailed description of this audio noise generator can be found in reference [44].

As seen in the emitted spectrum figures of section 3.1, the long-time emitted spectrum produced, using this audio noise generator as the modulating signal, is very similar to the one produced using the long-time voice signal (e.g., figures 3.6, 3.19, and 3.26). One would then expect to obtain protection ratio curves similar to the ones obtained with voice modulation when this audio noise generator is used as the modulation of the interfering signal. This is effectively correct, and can be seen in the comparison done in figures 3.55, 3.56, 3.57, and 3.58.

Measurements on these units lead to the following conclusion: using the 12 to 6 dB SINAD as the objective interference criteria, and voice or an audio noise generator as the modulating signal of the interfering channel, the protection ratios obtained are similar to the ones obtained using the subjective disruptive method of measurement.

Using the objective 12 to 6 dB SINAD as the method of evaluation, and the voice or an audio noise generator as the modulation of the interfering signal, it is now possible to obtain a close approximation of the disruptive interference protection ratio curves under automated computer controlled test set-up.

3.4.3 Signal Generators Instead of Transmitters

In an attempt to further simplify the measurement of the protection ratios for the various systems, the desired and undesired transmitters were replaced by signal generators. This would have the benefit of eliminating the shielded enclosures of the test set-up.

Using signal generators, the protection ratios of the MCX-FM units were measured as described above. The voice or an audio noise generator was used as the interfering modulating signal. A 1 kHz modulating tone was used as the desired signal. The amplitudes of the

modulating signals were set so that the peak deviation was 4.5 kHz for the 1 kHz tone, and would rarely exceed 4.5 kHz for the voice and the audio noise.

In figure 3.60, the objective protection ratios measured using the signal generators (SG) are compared with the objective protection ratios measured using the transmitters (TX, from figure 3.55). A subjective disruptive protection ratio curve (from figure 3.35) was also added to this figure.

Compared with the protection ratios obtained using the transmitters, one can see a difference of up to 25 dB with the ones measured using the signal generators. The protection ratio curves obtained using the signal generators follow the subjective curve outside the sloped regions, but differs a lot from it in the sloped regions.

Investigating further the reasons behind such a difference in the protection ratio curves, the long-time voice modulated spectrum at the output of the FM signal generator was displayed on the spectrum analyser, and is compared in figure 3.61 with the long time voice emitted spectrum obtained using the MCX-FM transmitter (from figure 3.4). One can see that the bandwidth of the RF waveform produced by the transmitter is wider than the one produced by the signal generator. This results from major differences in the design and performance of the respective equipments.

Although the differences in the use of signal generators instead of transmitters was not as obvious for FM, it is certainly for ACSSB and SSB. Generally, because of the high levels of spurious emissions produced by the power amplifier of the transceivers, nothing but the transmitters themselves can be used to represent the effective emitted spectrum. Even in the case of a single RF tone interfering, the differences in the emitted spectrum of a signal generator and of the transmitter produced slightly different protection ratio curves; this was seen for example in the case of the SSB transmitter, in figure 3.51.

Hence, one can conclude that for protection ratio measurements, the substitution of the transmitters by signal generators generally leads to smaller protection ratio results, and such a substitution can generally be considered as not giving representative protection ratios.

It has also been generally shown from the above sections that, in order to obtain similar disruptive protection curves, the long-time power spectrum of the interfering signal must be of the same general shape as the one produced by the voice modulated transmitter.

FIGURE 3.55 : MCX-FM, Comparison of Disruptive and Objective Methods

FIGURE 3.56 : STI-ACSSB into STI, Disruptive and Objective Criteria

FIGURE 3.57 : STI-ACSSB into MCX-FM, Disrup/Object. Comparison

FIGURE 3.58 : MCX-FM into STI-ACSSB Disrup/Object. Comparison

FIGURE 3.59 : STI-ACSSB into ICOM-FM, Disrup/Object. Comparison

FIGURE 3.60 : FM Comparison of Disrup/Object. using SG or TX

FIGURE 3.61 : Signal Generator and Transmitter Voice Spectrum

3.5 HARMFUL EFFECT OF SPURIOUS EMISSIONS ON THE DYNAMIC RANGE OF A RECEIVER

So far, it has been assumed in this study that the on-channel receiver could operate over its whole dynamic range (i.e., from the 12 dB SINAD sensitivity level up to the maximum input level, for example, from -120 dBm to +20 dBm). Furthermore, spectrum efficiency definitions generally assume that the adjacent channel interference on the on-channel frequency is low enough to allow the harmonious co-existence of these two stations within the same cell.

In this section, the effects of the spurious emissions of the adjacent stations on the dynamic range of a receiver and on the spectrum efficiency will be examined. First, our model is used to calculate propagation loss values, and levels of received signal. Using these results, the effect of the level of spurious emissions on the receiver is deduced.

3.5.1 Propagation Loss and Received Signal Level

Using the path loss equation and the radio communication model given in chapter 2, and used in section 3.3 to calculate the interfering distances, one can obtain a curve of the propagation loss and of the received power as a function of the geographical distance. Recall that for our model, the parameters had been assigned the following values:

- base 1 antenna height: 50 feet;
- base 2 antenna height: 50 feet;
- base 2 transmitted power: 25 watts;
- frequency: 150 Mhz.

The (base 1) received power in dBWatts, as a function of the geographical distance, is given directly by the first equation of section 2.3.4. By adding +30 to the calculated dBW value, the received power in dBm is obtained. Considering that the transmitter of base 2 is operating at 25 watts, the propagation loss can be derived by subtracting this value from the received one (i.e., Propagation loss = 44 dBm - received power in dBm). The propagation loss versus geographical distance curve obtained using this model is displayed in figure 3.62. Figure 3.63 shows the curve of the received signal level versus geographical distance. The reader is warned once more that these calculated values can differ substantially from the real life situation, and that they are used here only to illustrate the effect of some parameters on the communication link.

3.5.2 Effect of the Adjacent Channels Spurious Emissions on a Receiver

Taking for example the long-time voice emitted spectrum of the FM systems (figures 3.7 and 3.8), it was seen that the spurious emissions outside the 30 kHz bandwidth are about 70 dB below the maximum emitted power. Supposing, as used in our model, an emitted power of 25 watts (44 dBm), at the adjacent channel, the spurious emissions will have a level of about -26 dBm. In section 3.3, using our model, it was found that, to avoid disruptive interference, adjacent FM base stations should be geographically separated by about .5 to .67 miles. From the propagation loss curve (figure 3.62), one sees that at .7 miles geographical distance, the propagation loss between the two stations will be about 90 dB. Hence, the noise floor produced by an adjacent station transmitter, as seen by the on-channel receiver will be $44 - 70 - 90 = -116$ dBm. This is a few dB higher than the 12 dB SINAD sensitivity level of the FM systems. As a result, the dynamic range of these systems is being effectively reduced and their sensitivity degraded by the presence of the adjacent station.

Now let's assume, as it has been suggested in the past, that future radio systems are designed using a 40 dB bandwidth emitted spectrum rule for their channel spacing (instead of the 70 dB one, as seen, now used for the FM systems in the VHF). Using the same parameters as the ones used in the previous example, the on-channel receiver now sees the noise floor produced by the adjacent channel transmitter at $= 44 - 40 - 90 = -86$ dBm. In order for this receiver to detect a transmission from its mobile units, the signal received will have to be stronger than -86 dBm, instead of stronger than the 12 dB SINAD sensitivity level. That is, a degradation in the effective sensitivity, and in the dynamic range of the system of more than 30 dB.

In these 2 examples, the consequences of the degradation in the effective receiver sensitivity can also be approximately evaluated in terms of coverage area. With our model, this can be done using figure 3.63. At the limit, the usable area of the FM systems is a function of the 12 dB SINAD sensitivity level, i.e., about -120 dBm. From figure 3.63, the radius of this area is estimated at about 50 miles. A degradation to -116 dBm reduces this radius to about 40 miles. Finally, at -86 dBm, the radius is reduced to about 7 miles, making this station practically useless.

The same way, if the adjacent channel base stations are located closer to each other, this harmful effect will increase proportionally. At .1 miles geographical separation, the calculated propagation loss is about 55 dB. The noise floor produced by the adjacent channel

transmitter will then be $44-70-55 = -81$ dBm for a 70 dB bandwidth channel spacing, and $44-40-55 = -51$ dBm for a 40 dB bandwidth one.

From the above numbers, it is obvious that the level of the adjacent channel interference does play a very important role in the spectrum efficiency calculations; most spectrum efficiency models assume that adjacent stations can co-exist, and be co-located in the same cell. As seen with this model, this is not the case if the emitted spectrum is not contained within about a 70 dB bandwidth.

Finally, the effect of the spurious emissions on stations further separated in frequency can also be coarsely estimated. Using for example the 1 MHz span emitted spectrum as seen in figure 3.5, at 100 kHz from the transmitter, the interference level is about 85 dB below the maximum power. Using the same parameters as in the previous examples, the noise floor as seen by a co-located (.7 miles) receiver, 100 kHz away, would be: $44-85-90 = -131$ dBm, which is below the 12 dB SINAD sensitivity level of the FM receivers. If the geographical co-location was reduced to .3 miles, the noise floor would be $44-85-75 = -116$, which is higher than the 12 dB SINAD sensitivity level.

It can be seen from these examples, the importance, for any transmitter, to keep down its level of spurious emissions.

$T_x=25$ Watts, 50 feet, Rx 50 feet, $F=150$ Mhz

FIGURE 3.52 : Propagation Loss using our Model

Tx=25 Watts, 50 feet, Rx 50 feet, F=150 Mhz

FIGURE 3.63 : Received Signal Level using our Model

3.6 AUDIO FREQUENCY RESPONSES

In this section, the audio frequency response of some of the units under test are obtained. The frequency responses are obtained as a function of the RF signal level. The measurements were done on two FM systems: the MCX and the FORCE, on the STI-ACSSB, and on the ICOM-SSB.

3.6.1 General Considerations

The audio frequency response measured using the method described in the Radio Standards does not follow the usual definition of frequency response of a system, but rather verifies that *"the audio frequency response complies to a 6 dB per octave pre-/de-emphasis characteristic"* [117], or that *"the RF power output produced with constant amplitude audio frequency signal input over a continuous range of audio frequency does not vary"* [119].

With the increasing complexity of processing being done on the baseband signal, this kind of measurements is not necessarily representative of the real frequency response of the overall *system*. This will be demonstrated in this section.

By definition [138-139], for sinusoidal input frequencies over the range of interest, the frequency response of a *system* is given by i) the steady-state ratio of the output magnitude to the input magnitude, and ii) the output to input phase difference. The frequency response can be found experimentally by applying a sinusoidal signal of known phase and amplitude at the input of the system, and measuring the amplitude and phase characteristics at its output. The frequency is usually plotted on a logarithmic scale and the magnitude ratio (M) expressed in decibel ($M_{dB} = 20 \log_{10} M$).

For analog audio systems, the phase characteristic is not as important since it is often stated in acoustic that the human hear is practically insensitive to (linear) phase variations [140]. The performance of a system is therefore often based on achieving as much as possible a "flat" frequency response.

3.6.2 The Test

Applying the above concepts to a communication link, one has to consider it as a system, with the transmitter's microphone input consisting of the input of the system, and the receiver's speaker (i.e., audio amplifier output) as the output.

Hence, a "back to back" test arrangement (i.e., output of the transmitter feeding through proper attenuation—the antenna input of the receiver) will enable one to evaluate the frequency response of a communication system without giving any consideration to the processing done within it.

In this investigation, the audio frequency response was measured as a function of various RF signal levels. In this case, the amount of attenuation inserted between the transmitter and the receiver was set to obtain the desired RF signal level at the receiver's antenna input. The level of the single modulating audio tone was fixed, and its frequency was varied to cover the range of interest.

As seen previously, a frequency variation of the modulating signal will produce a different effect on the modulation parameters of the tested schemes: for FM, it will cause the modulation index to increase. For SSB no variation occurs, but for ACSSB, a small variation of the output power is caused due to the change in amplitude produced by the pre-emphasis of the signal.

Also, a variation of the level of the modulating signal will cause the frequency deviation of FM to increase (thus increasing the bandwidth of the RF transmitted signal). For both SSB and ACSSB it will have the effect of producing a proportional change of RF output power.

Various test instruments can be used to obtain the frequency response of a system. In our situation, the audio analyser utilized was providing the system's input reference audio tone (the source's level is flat over the range of frequencies), and had the (simultaneous) capability of measuring the amplitude and frequency of the system's output signal (i.e., after it had been through the transceivers under test). The audio analyser locks on and measures the strongest tone in the observed band. When the amplitude of the received tone (output of the system) is lost in noise, the frequency measurement yields a fast changing random value, and the amplitude measurement is the one of the noise level. This had the advantage of providing us with an additional parameter: the exact frequency at which the audio tone is lost in noise. This can happen either when the received RF signal level is very low, or when the modulating frequency is highly attenuated because it is out of the audio bandwidth of the system under test. Therefore, in addition to controlling the frequency response measurement,

the software developed for this test contained the following steps:

- 1- Read the system's output frequency on which the audio analyser locked on;
- 2- If the lock-on frequency is not the same as the one input to the transmitter, the measured value is set to -40 dB.
- 3- If the lock-on frequency is the same, proceed with the relative amplitude measurement.

3.6.3 Audio Frequency Response at Various RF Levels

The audio frequency response was measured with the RF output of the transmitter attenuated to yield at the receiver's antenna input an RF level of respectively -20, -40, -60, -80, -100, and -120 dBm.

One can set a reference level (such as 100 mV) at a particular frequency (such as 1 kHz), and monitor the change in level at the output of the system as the input frequency (which is flat) is changed. This reference can also be set as being equal to 0 dB; this is what was done for this measurement: the reference (0 dB) of the audio frequency response was taken as the level of the 1 kHz audio output at the receiver.

For FM, the frequency that produced the maximum deviation was first found, and its level was adjusted to produce a deviation of 4.5 kHz at the output of the transmitter. That same amplitude was used for all the other modulating frequencies. The maximum deviation for FM was obtained with a audio frequency of 2700 Hz. For SSB and ACSSB, the level of the modulating tone was adjusted to produce rated PEP. But, for ACSSB, the frequency that produced the highest emitted power was first found (500 Hz in our case), and its level was adjusted to produce rated PEP. That same level was used for all the other modulating frequencies.

Figures 3.64, 3.65, 3.66, and 3.67 show the audio frequency response at various RF signal levels, respectively for the MCX-FM, FORCE-FM, STI-ACSSB, and ICOM-SSB. No smoothing was applied to the data when the curve was plotted so that the -40 dB relative value assigned when the signal is lost into the noise is displayed on the figures as a sharp drop in relative amplitude. Frequency response values were measured every 100 Hz, except at the extremities of the audio bandwidth of the systems, where it was taken every 25 Hz.

Except for the SSB unit, the frequency response does not change very much for RF output signal levels from -20 to -100 dBm. For the SSB unit, the frequency response gets

narrower starting with an RF signal level of -80 dBm. For the 4 tested units, at weak RF levels (below -100 dBm), some audio frequencies get lost into the noise (i.e., the noise is higher than the tone measured). Note that for the STI-ACSSB unit, -120 dBm is 10 dB below the 12 dB SINAD sensitivity level.

In figure 3.68, a comparison of the frequency response at a RF level of -40 dBm is displayed for the 4 units. Table 16 shows the 3 dB cut-off frequencies, and Table 17, the 10 dB cut-off frequencies at this RF level of -40 dBm.

One notes that the MCX-FM has the widest bandwidth, but that the FORCE-FM and the STI-ACSSB have a very similar 3 dB cut-off bandwidths. The ICOM-SSB is the one with the lowest low and lowest high cut-off frequency.

As seen in figure 3.68, the MCX-FM frequency response is the best of the 4 compared systems: it has a close to flat response (+0.7 to -0.9 dB) between 400 to 1500 Hz; for both the STI-ACSSB and the FORCE-FM, the frequency response is not as good: in that 400-1500 Hz range, it varies by about +2 to -7 dB for the STI-ACSSB and about +.7 to -5 dB for the FORCE-FM. For SSB, the same region, although not as flat as for the MCX-FM, can be considered as being relatively good (+1.5 to -1.8 dB variation). The attenuation of the frequencies outside their audio bandwidth is relatively smooth for all the units, except for the SSB one (this is shown by the sharp drop to -40 dB mentioned earlier).

A measure of the "audio frequency response" made according to the method described in the respective radio standard specifications of each unit (the TRC-72 was used for ACSSB) showed that these units were conforming to the minimum performance standard. Thus, the inadequacy of the method of measurement, used in these radio standards, to provide a real evaluation of the input/output audio transfer characteristic of these systems is demonstrated by the above results.

It is consequently suggested that future Radio Standards be less concerned about specifying the kind of processing done within a system (e.g., the exact amount of pre /de emphasis),⁶ but rather concentrates on evaluating its overall performances.

⁶ As per the RSS-119, FM must have a 6 dB per octave pre-emphasis and a 6 dB per octave de-emphasis; but what if a manufacturer find out that a 12 dB per octave would perform better for its system? The STI-ACSSB Service Manual (Pioneer 1000, Mobile Transceiver Front Mount, First Edition, July 1982) show a 12 dB per octave pre-emphasis (page 4-35), and only a 6 dB de-emphasis (page 4-28). Hence, until experience has shown what are the optimal conditions, the kind of audio processing done within a system should not be limited by a Radio Standard.

Generally, one notes that the FM systems have a better frequency response than the SSB and ACSSB systems. Consequently, in a voice quality comparison between FM and ACSSB, FM would show a better performance than ACSSB. Hence, the better voice quality, over SSB or ACSSB, credited in the past to FM, should not necessarily be attributed to the difference in the modulation schemes. Since, as seen from table 16, a particular FM system has a 3 dB .at. off frequency response of 200 to 2250 Hz, the ACSSB has one of 625 to 2050 Hz, and the SSB 165 to 1750 Hz. Consequently, the difference observed, in some studies, between the voice quality of these schemes could be in some part attributed to the difference in their audio frequency responses.

UNIT	Lower 3 dB cut-off Fr.	Upper 3 dB cut-off Fr.
MCX-FM	200	2250
FORCE-FM	550	2050
STI-ACSSB	625	2050
ICOM-SSB	165	1750

TABLE-16: Audio Frequency Response: 3 dB Cut-off Frequencies

UNIT	Lower 10 dB cut-off Freq.	Upper 10 dB cut-off Freq.
MCX-FM	155	3450
FORCE-FM	270	3150
STI-ACSSB	350	2310
ICOM-SSB	140	2550

TABLE-17: Audio Frequency Response 10 dB Cut-off Frequencies

FIGURE 3.64 : MCX-FM Audio Frequency Response at various RF levels

FIGURE 3-65 : FORCE-FM Audio Frequency Response at various RF levels

FIGURE 3.66 : STI-ACSSB Audio Frequency Response at various RF levels

FIGURE 3.67 : ICOM-SSB Audio Frequency Response at various RF levels

FIGURE 3.68 : Audio Frequency Response for the 4 Units, RF=-40 dBm

3.7 SPECTRUM EFFICIENCY OF FM, ACSSB, AND SSB

3.7.1 Introduction

As seen previously, spectrum efficiency was defined as a measure of the number of users per unit area per Hz that can use the service with a given quality of communications. The honeycomb structure model was used to define the important spectrum efficiency parameters of the land mobile environment. Using this model, it was shown that the channel spacing and the re-use distance of a channel frequency were the two most critical parameters, since the interfering distance relates directly to the number of users per unit area, and the channel spacing relates to the number of users per unit spectrum. It was shown that the channel spacing can not be assigned based solely on the emitted spectrum of the systems, but that the resistance to interference of the receiver, i.e., its protection ratios, also played a role. For the re-use distance, it was shown that the protection ratio was not the only element to consider in the evaluation of the co-channel interfering distances, but that the receiver sensitivity had also to be taken into consideration in this calculation. Moreover, it was shown that the spectrum efficiency calculation for various systems should only be made when similar or equivalent testing conditions and criteria are used for all the tested systems. Also, it was assumed that the receivers did not suffer interference from communications carried on at the adjacent channel frequencies.

For the evaluation of the channel spacing and of the re-used distance, it was shown that a number of evaluation criteria existed. Measurements made using various interference criteria showed that the protection ratios vary a lot from one criteria to the other. Because the subjective disruptive interference gives a measure of the limit of intelligible operation of the system, this criteria was chosen as the most useful one for the protection ratio measurement in the land mobile communications environment.

In the comparison of the emitted spectrum of the various systems, the long-time voice modulated emitted spectrum was chosen as the comparison criteria, because this spectrum represents the worst case situation, and because the systems under test are used to transmit voice, not tones.

Finally, since the spectrum efficiency evaluation is also based on a given quality of communications, the compared systems should have a similar audio quality.

3.7.2 Spectrum Efficiency Evaluation

In the past, some studies have evaluated the audio quality of SSB and ACSSB as slightly inferior to the FM one. It was shown in this study that the difference in quality could be attributed in part to the difference in the frequency response of the tested systems. Since an improved design of the audio section for the linear schemes does not present any difficulty, the audio quality will not be introduced here as being entirely different for the various schemes, but rather as providing a similar quality of communications.

Based strictly on the long-time voice emitted spectrum, FM was shown to have a 70 dB bandwidth at 30 kHz. This bandwidth represents the level of interference on the adjacent channel. In order to obtain the same kind of performances in terms of interference level and dynamic range for co-located adjacent stations, the channel spacing of any new system that is to be introduced in the same band (VHF) should also be based on its 70 dB bandwidth.

The 70 dB bandwidth for ACSSB was obtained with a channel spacing of about 13 kHz. If this criteria was lowered to 66 dB, 10 kHz channel spacing would be obtained. For SSB, the 70 dB bandwidth yielded a 15 kHz channel spacing. A 60 dB bandwidth was reached for a 10 kHz channel spacing.

Using the disruptive interference criteria, the adjacent channel protection ratios for FM were in the range of -74 to -82 dB. Assuming that any new system introduced in the VHF should have similar adjacent channel protection ratios, it was found that a channel spacing of 10 kHz for protection ratio of -71 dB was obtained for ACSSB. At a channel spacing of 9 kHz for SSB, the disruptive interference protection ratio is also -71 dB.

In terms of disruptive adjacent channel interfering distances, applying the same model to the various schemes, required geographical separation of .5 to .7 miles for FM, .5 miles for ACSSB, and 1.1 miles for SSB were obtained. A disruptive protection ratio of -84 dB, obtained with a 12.5 kHz spacing, yielded .5 miles for SSB.

The disruptive protection ratios for the co channel situation were 7 to 8 dB for FM, 5 dB for ACSSB, and -1 dB for SSB. The calculated disruptive re-use distances were respectively 70 to 89 miles for FM, 39 miles for ACSSB, and 63 miles for SSB. The small re-use distance for ACSSB as well as the relatively large variations in the calculated distances for FM were shown to be related to the receiver's 12 dB SINAD sensitivity level of each system.

Using the above values, the spectrum efficiency of each scheme can now be evaluated. Let's consider first the channel spacing parameter. The long-time voice emitted spectrum of ACSSB has a 66 dB bandwidth at 10 kHz channel spacing. A -71 dB disruptive adjacent channel protection ratio is also obtained for a 10 kHz channel spacing. This compares relatively well with the -70 dB protection ratio and the 70 dB bandwidth rule found for FM at 30 kHz channel spacing. Also, for these channel spacing values, the calculated disruptive adjacent channel interfering distances were .5 to .7 miles for FM and .5 miles for ACSSB. Since these results for 10 kHz ACSSB channel spacing compare well with the 30 kHz FM ones, it is concluded that 3 times more channels can be provided by ACSSB than by FM.

The calculated disruptive interference re-use distance for FM was between 70 to 89 miles, depending on the system, yielding an interference area (πd_s^2) of 15394 to 24885 square miles. For the ACSSB under test, the calculated re-use distance was 39 miles, and the interference area, 4778 square miles. Hence, between 3.2 to 5.2 more ACSSB stations could be put into the area occupied by one FM station. Assuming the worst case situation, a value of 3 will be used in the evaluation below.

Overall, ACSSB is therefore a minimum of 9 times more spectrally efficient than FM. That is, considering both the re-use distance and the channel spacing advantages, 9 ACSSB stations of the type tested could be put in the area used by one FM station.

Should an ACSSB system be designed with a receiver's 12 dB SINAD sensitivity similar to the FM systems, the re-use distances would become relatively similar to the FM ones, and the spectrum efficiency advantage would decrease to only that of the channel spacing ratios, i.e., 3 times more efficient. Also, should an improved linear power amplifier be used, along with sharper selectivity filters in the receiver, the channel spacing of ACSSB could be further reduced, and the spectrum efficiency would increase accordingly.

For SSB, a -71 dB disruptive adjacent channel protection ratio is obtained for a 9 kHz channel spacing, but the long-time voice emitted spectrum has a 70 dB bandwidth at 15 kHz channel spacing. For 10 kHz channel spacing, a 60 dB bandwidth is obtained. Also, for these channel spacing values, the calculated disruptive adjacent channel interfering distance is about 1.1 miles for SSB; it was .5 to .7 miles for 30 kHz FM. A disruptive protection ratio of -84 dB, obtained with a 12.5 kHz spacing, yields .5 miles for SSB. Accepting some degradation in the dynamic range and more interference from the adjacent channel stations,

a 10 kHz channel spacing can be used for our calculations, yielding, as for ACSSB, about 3 times more channels for SSB than for FM.

The calculated disruptive interference re-use distance for SSB is in the same range as the ones obtained for FM. Consequently, basically no advantage in spectrum efficiency is obtained with this parameter. Overall, SSB is therefore about 3 times more spectrally efficient than FM.

Although not normally used as such in the spectrum efficiency calculations, additional stations can be added in the form of interstitial channel (i.e., at half the channel spacing). For FM, at 15 kHz, disruptive protection ratios of the order of -19 to -34 dB were measured, with calculated interfering distances of 8 to 17 miles. For ACSSB at 5 kHz, these values were -37 dB and 3.5 miles. For SSB at 5 kHz, -52 dB and 3.4 miles. Thus, it can be concluded that both ACSSB and SSB have an advantage over FM in terms of lower geographical distances required for the assignment of interstitial stations.

CHAPTER 4

CONCLUSIONS

4.1 SUMMARY

It is well known that the existing spectrum allocation in the land mobile radio bands has become saturated. There is a need for more channel allocations, but no more spectrum is available. The analog voice modulation systems presently used in the VHF and UHF bands utilized Frequency Modulation and a RF channel spacing of the order of 25 to 30 kHz per station. A smaller channel spacing, made possible by more spectrally efficient signalling techniques (e.g., linear modulation such as SSB), is one of the solutions that could help solve the spectral congestion problem. Recently, commercial ACSSB systems have appeared on the market, and their introduction in the VHF band, with a channel spacing of 5 kHz, has been suggested. However, the possible spectral advantage of ACSSB compared to FM in this band has not been clearly established, due to the incommensurability of the few available studies, and due to the various interpretation of spectrum efficiency. Consequently, some of the goals of this study were to compare the VHF FM, SSB, and ACSSB schemes using uniform testing methods, to define the most appropriate measurement techniques and criteria that should be used for this comparative evaluation, and to identify the important parameters that should be considered in the spectrum efficiency calculation and in the channel spacing determination.

In section 2.1, the honeycomb structure model was used to show that the channel spacing is not the only important factor governing spectrum utilization, but that the geographical re-use distance of a channel also plays a very important role.

As a first step towards uniformization of the testing methods, the available receiver's sensitivity evaluation measurement methods were described and compared (section 2.2). The SINAD sensitivity evaluation was chosen as the most appropriate one, and a SINAD measurement method was established for the ACSSB systems (section 3.2). The measured

12 dB SINAD for the 3 different FM systems under test were between -118.5 to -121.5 dBm. For the SSB unit, it was -124.5 dBm, and for the ACSSB, -110 dBm.

In section 2.3, the necessary background required for an interference analysis between the various modulation schemes was presented.

In section 3.1, the emitted spectra of the commercial VHF FM, ACSSB, and SSB units were obtained under various modulating conditions. For FM, using the long-time voice modulated emitted spectrum (i.e., worst-case emitted spectra), it was seen that the relative average power of the frequency components outside the FM assigned channel bandwidth was about 70 dB below the maximum power. This value was down to 30 dB for the interstitial channel situation (15 kHz away). Hence, for FM in the VHF band, the worst-case emitted spectrum in a 30 kHz channel spacing was said to have a 70 dB bandwidth, and a 30 dB one for the 15 kHz situation.

It was shown that, although not usually introduced as a parameter in the calculation of the spectrum efficiency, this 70 dB bandwidth, representing the level of interference on the adjacent channel, becomes a factor that has to be considered when one wants to introduce new systems in the VHF band. Since, in order to obtain the same kind of performance in terms of interference level and dynamic range for co-located adjacent stations, the channel spacing of the new systems should also be based on their 70 dB bandwidth. More generally, as was shown in section 3.5, if less severe emitted bandwidth restrictions are accepted, the interference from the adjacent stations becomes too high, and adjacent station frequencies can not be used in the same cell, thereby effectively reducing the spectrum efficiency by a factor of 2.

From the long-time voice emitted spectra of the tested ACSSB units, it was shown that the 70 dB bandwidth was obtained with a channel spacing of about 13 kHz. If this criteria was lowered to 66 dB, 10 kHz channel spacing would be obtained. For the 5 kHz channel spacing suggested for these units, this values was down to about 40 dB.

Comparing the ACSSB and SSB transmissions, it was shown that, under similar modulating conditions, their emitted spectra did not differ substantially. It was consequently concluded that no significant improvement, regarding the intermodulation distortion caused by the non-linearities of the power amplifier, had been made for the ACSSB transmitters. By applying the 70 dB bandwidth to the long-time voice emitted spectrum of SSB, it was shown that SSB would yield slightly larger channel spacing than ACSSB: of the order of 15

kHz. At 10 kHz channel spacing, the spectra would meet at about 60 dB below the rated PEP. As for ACSSB, when the SSB spectra are spaced 5 kHz apart, they crossed at about 40 dB below PEP.

For the 3 modulation schemes under test, it was shown that when an audio noise generator, with a spectral response that simulates the long term power density spectrum of continuous speech, is used as the modulating signal, the resulting long-time emitted spectrum is similar to the one produced with voice modulation.

A suggested immediate implementation of ACSSB in the VHF band is to insert ACSSB channels between the presently allocated FM channels. Strictly based on the emitted spectra, it was shown that an interstitial ACSSB station would cause too much interference on the FM for them to be co-located. On the other hand, less geographical separation would be required for an interstitial ACSSB compared to an interstitial FM.

It was also shown that if a hypothetical ACSSB system with a 70 dB bandwidth emitted spectrum smaller than 5 kHz was inserted between the 2 FM stations, the level of interference on the FM stations would be relatively close to the one produced by adjacent FM stations, therefore causing little degradation to the existing FM systems in the VHF band.

A general interference and protection ratios study between the systems was done in section 3.3. In that section, objective and subjective measurements similar to the ones that have generally been used in the past in various interference studies, or that are being currently used by some radio standards, were done on the systems under test.

FM into FM interference measurements were reported in section 3.3.3. Using the RSS-119 two signal selectivity measure, the protection ratios for the 3 tested FM systems was found to vary from about 5 to 9 dB at the on-channel frequency, and from about -34 to -58 at the interstitial frequency. At 20 kHz, the protection ratios were smaller than -70 dB, and at 30 kHz, smaller than -75 dB.

The subjective measures always yielded protection ratio curves wider (i.e., worse) than the ones obtained with the two signal selectivity objective measure. In general, a very large difference was observed, for all frequency separations, in the protection ratios obtained using different criteria. It was shown that the interfering signal as well as the interference criteria used, both played a very important role in the value of the protection ratio obtained, and that comparing protection ratios obtained from various studies, where

different interference criteria and different interfering signals were used, could only yield incommensurable results.

Also, by testing 3 different FM receivers of the same type (i.e., from 3 different manufacturers), it was shown that in an experimental interference evaluation, the protection ratios obtained can basically only apply to the specific tested units. Except for the co-channel frequency, generalizing the results obtained using only one system can be misleading. This conclusion applied to both the objective and subjective measures.

Re-use distances are often calculated using exclusively the co-channel interference protection ratio. In spite of the fact that the disruptive co-channel protection ratio values for the 3 different tested FM systems were about the same, the difference between their calculated interfering distances was large, of the order of 20 miles (from 70 to 89 miles). It was seen that the re-use distance can not be computed using exclusively the protection ratios, as it has been often done in the past. The sensitivity of the receiver has to be taken into account, since it too plays an important role in the extent of the denied area.

ACSSB into ACSSB interference measurements were reported in section 3.3.5. Generally, because of the receiver design differences related to a smaller bandwidth, the width of the ACSSB protection ratio curves was narrower than that of FM. Although having relatively similar co-channel protection ratios to that of FM, the calculated interfering distances of ACSSB into ACSSB were much lower than the ones obtained for FM into FM (39 miles for ACSSB versus 70 to 89 miles for FM). This was explained by the fact that the 12 dB SINAD sensitivity for the ACSSB units is higher (worse) than the ones of the FM units. This poor sensitivity of ACSSB could also explain why some studies have found the coverage area of ACSSB to be smaller than that of FM. At adjacent channel spacing (30 kHz), the lowest disruptive interfering distance calculated with our model was 0.5 mile for FM. The 0.5 mile disruptive interfering distance for ACSSB was obtained at a frequency separation of 10 kHz. A geographical separation of about 3.5 miles was required for 2 adjacent ACSSB with a 5 kHz channel spacing.

The margin between the disruptive and the just noticeable interference cases was smaller for ACSSB than for FM. This was considered advantageous, since an "interference free" criteria would be easier to apply with the ACSSB systems than with the FM ones.

Using the disruptive interference criteria, and assuming an adjacent channel protection ratio for ACSSB similar to the ones obtained in this situation for FM, a channel spacing of about 10 kHz (for protection ratio of the order of -70 dB) was found for ACSSB.

In the past, the two signal selectivity curves have been sometimes used as a means of comparing the protection ratios of FM and ACSSB. It was shown that this comparison was not valid since the two signal selectivity curve is very close to the disruptive interference one for ACSSB but is not for FM.

Measurements to obtain the protection ratios of FM interfering into ACSSB were reported in section 3.3.6. The ACSSB system was shown to be less affected by a co-channel FM interfering signal than it was by a co-channel ACSSB one. It was also shown that one ACSSB inserted halfway (15 kHz) between two adjacent FM stations would be relatively resistant to the interference produced by the FM stations, and it was concluded that, from the ACSSB point of view, one interstitial ACSSB, between 2 FM, would be viable, in the context of the present frequency allocation scheme. This conclusion did not hold when 2 ACSSB stations, 5 kHz between them, were inserted between 2 adjacent FM stations.

ACSSB into FM interference measurements were reported in section 3.3.7. As in the case of FM into ACSSB, the FM units were less affected by a co-channel ACSSB interfering station than it was by a co-channel FM one. Thus, it was concluded that both the FM and the ACSSB systems resisted better to co-channel interference from foreign modulation schemes than to their own.

It was shown that the FM systems were more affected by the interstitial presence of the ACSSB than the ACSSB was of the FM, and it was concluded that from the FM point of view, one interstitial ACSSB, between 2 FM systems, was not acceptable, in the context of the present frequency allocation scheme. On the other hand, extrapolating the protection ratio results to a hypothetical 5 kHz, 70 dB bandwidth channel for ACSSB, it was shown that the FM stations would still suffer slightly from the insertion of this smaller bandwidth interstitial channel, but that the degradation could be considered acceptable. Consequently, the possibility of inserting narrowband technologies between existing VHF FM stations still exists, as long as the interstitial station has a 70 dB bandwidth emitted spectrum equal to or smaller than 5 kHz.

Finally, in order to complete the comparison between the modulation schemes tested in this study, a few interference measurements were done with the SSB units (section 3.3.9).

Using the -70 dB disruptive protection ratio criteria found for adjacent channels FM, the required channel spacing for SSB was evaluated to be about 9 kHz.

Because of the better 12 dB SINAD sensitivity of the SSB receivers, the calculated interfering distances for SSB into SSB were higher than the ACSSB into ACSSB ones (e.g., ACSSB disruptive re-use distance = 39 miles, SSB = 63 miles). But the disruptive interfering distances of ACSSB into FM were a bit larger than the SSB into FM ones, probably because of the wider emitted spectrum of ACSSB compared with the SSB one.

In section 3.4, a comparison was done between the various objective and subjective measures reported in section 3.3. Using these results, a new objective measurement method was derived: using a 1 kHz audio tone as the on-channel signal, and interfering with voice, the SINAD degradation of the on-channel signal was measured. A number of tests were done using this method, and a degradation of 15 to 12 dB SINAD, as well as a 12 to 6 dB SINAD one were used as criteria. The protection ratios obtained using this objective method were compared with the subjective disruptive ones. The 15 to 12 dB SINAD method did not yield results that were similar enough to the subjective disruptive interference case to be considered as adequate. But the 12 to 6 dB SINAD measure did. It was shown that, when compared using the same interfering (undesired) signal (i.e., voice), the protection ratios obtained with a 12 to 6 dB SINAD objective measure are similar to the ones obtained with the subjective disruptive interference criteria.

Also, an audio noise generator with a spectral response that simulates the long term power density spectrum of continuous speech was tried instead of the voice signal in this 12 to 6 dB SINAD objective measure. The results obtained using the noise generator as the modulation of the interfering signal were similar to those obtained with voice modulation.

Finally, it was shown that for the protection ratio measures, the substitution of the transmitters by signal generators generally leads to smaller protection ratio results, and such a substitution could generally be considered as not giving representative protection ratios.

In section 3.6, the audio frequency responses of some of the units under test were obtained. Generally, the FM systems had a better frequency response than the SSB and ACSSB systems. Hence, in a voice quality comparison between FM and ACSSB, it was concluded that FM would show a better performance than ACSSB. Therefore, it was noted that the better voice quality over SSB or ACSSB, credited in the past to FM, should not

necessarily be attributed to the difference in the modulation schemes, but could also be in part attributed to the difference in their audio frequency responses.

In section 3.7, the spectrum efficiency of each scheme was evaluated. Overall, ACSSB was estimated to be a minimum of 9 times more spectrally efficient than FM. That is, considering both the re-use distance and the channel spacing advantages, 9 ACSSB stations of the type tested could be put in the area used by one FM station. It was also shown that if an ACSSB system was designed with a receiver's 12 dB SINAD sensitivity similar to the FM systems, the re-use distance would become relatively similar to the FM ones, and the spectrum efficiency advantage would decrease to only that of the channel spacing ratios, i.e., 3 times more efficient. It was noted that if an improved linear power amplifier was used, along with sharper selectivity filters in the receiver, the channel spacing of ACSSB could be further reduced, and the spectrum efficiency would increase accordingly. SSB was estimated to be about 3 times more spectrally efficient than FM. It was also shown that both ACSSB and SSB had an advantage over FM in terms of lower geographical distances required for the assignment of interstitial stations.

4.2 CONCLUSIONS

As mentioned at the beginning of this study, due to the incommensurability of the few available studies, and due to the various interpretation of spectrum efficiency, the possible spectral advantage of ACSSB compared to FM in the VHF band had not been clearly established. This study clearly shows that ACSSB is more spectrally efficient than FM. Some of the factors that have contributed to this confusion have been identified, and solutions to avoid these problems in the future were presented. Conclusions obtained for the ACSSB systems in the VHF band were also extended to cover some of the factors that should be generally considered in the introduction of new technologies in existing bands.

Two major parameters were found to be critical in establishing the channel spacing: the level of the emission on, and the level of protection of the adjacent channel. As a result, the initial 5 kHz channel spacing suggested for ACSSB was found not to be enough to support the restrictions imposed by the existing systems used in the VHF band, and a 10 kHz channel spacing was determined as being more appropriate.

The fact that a system having a channel spacing x times smaller than another one, has often been used solely in the past, as a way of comparing the spectrum efficiency of different systems. This study demonstrated that this is true only when the comparison

is made using systems that have comparable re-use distances and comparable quality of communications. It was also pointed out that the re-use distance can not be calculated using only the protection ratio, but that the receiver's sensitivity also had to be taken into account.

It has been suggested in the past to use the performance criteria outlined in the HF SSB radio standard as a basis to build narrowband equipment for the other bands (VHF and UHF). It was shown in this study that this leads to transceivers that do not comply with the standards for the VHF and UHF bands, unless their channel spacing is increased. Ideally, regulations should exist that specify the minimum performance criteria required for new technologies, so that the manufacturers of communication systems know from the start the specifications their systems will have to meet. Also, it was found that radio standard specifications put too much restrictions on some specifications, so that the manufacturers do not have room to implement improved techniques, or can not introduce new technologies. For example, specifying that in the VHF band, FM at 30 kHz must be used, does not leave room for creativity. Specifying instead (among other things) that any system that has a 70 dB long-time voice emitted spectrum in a bandwidth that is an integer submultiple of 30 kHz, might encourage some manufacturers to look for new technologies. In a similar way, instead of specifying the actual level of pre/de-emphasis required, a more general frequency response measurement, such as obtained in a back-to-back test situation, would leave the manufacturers free to implement processing in the way they feel will provide the best audio quality. Also, some of the testing conditions of the radio standards were found to be not representative of the land mobile radio environment. Since voice modulation is normally used with these systems, this modulation, or an equivalent form, such as the one obtained with an audio noise generator, should be used, instead of a 1 kHz modulating tone, for testing. Long-time voice modulated emitted spectrum and disruptive interference criteria were suggested as methods of evaluation more representative than the ones presently used. Moreover, the use of the actual transmitters instead of RF signal generators would also lead to a more representative evaluation.

A major deterrent towards immediate usage of the narrowband technologies is that there is FM equipment presently operating in the field with a life expectancy of more than 10 years. So the phasing out operation can only be made over many years. The co-existence of the old and new technologies then become an essential factor to be considered. It has been

suggested in the past that the new technologies could be inserted at the interstitial frequencies (15 kHz) of the existing 30 kHz channel spacing FM systems. This would have the advantage of immediately doubling the number of available stations in the VHF band. Using the results of this study, it was seen that ACSSB would not suffer from such an assignment, but it was also shown that generally, FM could not support the presently available ACSSB systems without suffering degradation. A solution would be to impose more severe specifications to the FM systems, but this retort to the same problem as introducing new technologies. Hence, the introduction of the 10 kHz channel spacing ACSSB at the interstitial frequencies could generally be made only using geographical separation. But, if a narrower channel spacing technology was used, a slight degradation would still occur, but, as seen, could be considered acceptable. Thus, the insertion of new technologies between existing FM in the VHF band could still be a practical solution in the future, when narrower emitted spectrum (5 kHz or less, 70 dB bandwidth) technologies are introduced. ACSSB with an ultra-linear amplifier could provide a solution here. Note also that, contrary to what has been suggested in the past, the results of this study show that only one (not two) narrowband station could be inserted between existing FM in the VHF band.

Using presently available commercial units, the only other way to introduce these new technologies is by phasing out the 30 kHz FM, and replacing them with the narrower channel spacing systems. That is, when a user has to change his equipment, or when an assigned frequency becomes available, incentives or regulations should exist so that the change is made to a smaller channel spacing system. For example, using the 10 kHz ACSSB system evaluated in this study, 3 stations can be inserted in the bandwidth occupied by the 30 kHz FM. Adjacent ACSSB would have an interference performance similar to that of FM, and the adjacent FM channels would suffer a degradation similar to the one obtained with an all FM frequency allocation.

Also, a user that now has a license for 30 kHz should be encouraged to use a smaller channel spacing system. Many operations, because of expansion for example, would presently like to increase their number of available stations. A three fold increase is presently feasible with the commercial ACSSB systems. The users should be clearly presented this solution as a way to solve their problems.

Because the VHF and UHF frequency bands have often been qualified as the best ones for land mobile usage, it would be reasonable to take full advantage of these bands by

increasing the number of users that can utilize them; the developments presented in this study, as well as other techniques being presently investigated, represent an efficient and adequate narrowband alternative to FM, and could make this possible.

4.3 FUTURE WORK

Since the sensitivity of a receiver is a parameter that can be relatively easily controlled in the design process, the results of this study showed that this characteristic of a receiver could be better used in future designs to reduce the re-use distance, and therefore increase the spectrum efficiency. As seen for FM, the large range of the calculated re-use distances (70 to 89 miles), for different FM systems of the same type, was exclusively due to the differences in sensitivity of the receiver of each system. Also, for ACSSB, the small re-use distance (39 miles) was also attributed to the poor 12 dB SINAD sensitivity of the receiver. But in the case of ACSSB, the poor sensitivity can be considered disadvantageous because more emitted power would be required to achieve the same coverage as for FM. A balance between the level of emitted power and the receiver's sensitivity has to be achieved, since, in the case of introducing new systems in a band already saturated, too much emitted power will necessarily have an adverse effect on the existing systems used in this band.

Consequently, a study of the needs of the users would be useful in showing what minimum coverage area is generally required, and the systems could be designed to support only this area, since, as was seen in the spectrum efficiency calculations, the product of the density ratio (base station per square mile) by the channel spacing ratio yields a spectrum efficiency factor many times larger than that obtained only with a reduction of the channel spacing. This is one of the reason why cellular schemes are so spectrum efficient.

It has generally been the practice in the past for manufacturers to design receivers with the best possible sensitivity. As shown in this study, this is not necessarily advantageous, since the most sensitive receivers will be more affected by the interference from the co-channel stations. If all the receivers had the same 12 dB SINAD sensitivity, frequency assignment could be made with more precision. Also, if the spurious emissions of the adjacent channel stations are allowed to increase, the noise floor (produced by the adjacent transmitters) as seen by the receivers will be higher than the 12 dB SINAD sensitivity, making a good receiver's sensitivity useless. Further studies and regulation in this area could therefore be advantageous.

The 12.5 kHz narrowband FM has also been suggested in order to increase the number of available stations in the land mobile bands. Measurements of the long-time voice emitted spectrum and of the disruptive protection ratios will be required to determine if these 12.5 kHz systems can co-exist harmoniously with the present 30 kHz FM ones. Similarly, a study establishing these parameters will be required for the 25 kHz channel spacing FM systems used in the UHF band. Since the introduction of new technologies in this band will probably follow a pattern similar to that of the VHF band, the long-time voice emitted bandwidth and the level of the disruptive adjacent channel protection ratio will be needed to determine the effects of new technologies on the 25 kHz FM one.

As was shown by the large variation of the results obtained in the measured protection ratios and calculated interfering distances for the 3 tested FM systems of the same type, a study involving more ACSSB and SSB systems, produced by different manufacturers, would be necessary in order to generalize the results obtained for them. Also, in order to obtain generalized results, more listeners should be used in the subjective tests, and both male and female speakers should be used for the modulating signal.

Finally, if no systems already existed in a given frequency band, could the 70 dB long time voice emitted spectrum bandwidth and the -70 dB disruptive adjacent channel protection ratio criteria be lowered? Basically, they could, but, as seen, a degradation in performances will necessarily result: the dynamic range and the interference rejection of co-located adjacent stations will be reduced. Even if receivers with sharper selectivity were designed to try to compensate for the higher interference, the effective sensitivity degradation of the receiver caused by higher adjacent channel spurious emissions can be hardly avoided, since there is also a necessity to keep relatively low the geographical separation of co-located adjacent stations. Neither of these two parameters, the dynamic range, nor the co-located geographical separation, are usually included in spectrum efficiency calculations. Hence, any increase in the level of permitted adjacent channel interference should be done very carefully, considering the effects it has on the performance of the systems and on the spectrum efficiency. Further studies in this area, using a more accurate model or using field trials, would help in establishing more precise guidelines.

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APPENDIX A

Manufacturer's Specifications of the Tested Systems

MOTOROLA MCX 100

SPECIFICATIONS

GENERAL

Number of Frequencies	Up to 32 channels, synthesized
Type of Squelch	1000 Series: Carrier Squelch 7000 Series: Private-Line and Digital Private-Line 9000 Series: Select 5
Primary Power	12 V dc nominal, negative ground
Dimensions	6-10 Watt Models: 22.8cm L x 17.9cm W x 5.1cm H (8 9/16" L x 7 1/8" W x 2" H) 25-30 Watt Models: 27.9cm L x 17.9cm W x 5.1cm H (10 9/16" L x 7 1/8" W x 2" H)
Weight	6-10 Watt Models: 2.9kg (6.4 lb) 25-30 Watt Models: 3.2kg (7 lb)

Typical Battery Current Drain (Less Options)

Model Series	Minimum RF Power Output	Frequency Range (MHz)	Standby @13.8 V	Receive at Rated Audio @13.8 V	Transmit at Rated Power @13.8 V
D-1131 MA	6 Watts	146 — 174	350 mA	1.1A	2.5A
D-1231 MA	10 Watts	146 — 174	350 mA	1.1A	3.0A
D-1331 MA	25 Watts	146 — 174	350 mA	1.1A	7.0A
D-1231 CUA	10 Watts	136 — 174	350 mA	1.1A	3.0A
D-1431 CUA	30 Watts	136 — 174	350 mA	1.1A	7.5A

TRANSMITTER

Output Impedance	50 Ohms
Frequency Stability	EMA Series: $\pm 0.001\%$ from -25°C to $+60^{\circ}\text{C}$ ($\pm 0.0005\%$ and $\pm 0.0002\%$ optional) (+ 25°C reference) CUA Series: $\pm 0.0005\%$ from -30°C to $+60^{\circ}\text{C}$ ($\pm 0.001\%$ and $\pm 0.0002\%$ optional) (+ 25°C reference)
Spurious and Harmonics	6-10 Watt Models: 80 dB below carrier 25/30 Watt Models: 85 dB below carrier (less than 2×10^{-7} watts all models)
Modulation	(16F3) ± 5 kHz for 100% @1000 Hz (25/30 kHz and Japan) ± 2.5 kHz for 100% @1000 Hz (12.5 kHz) ± 4 kHz for 100% @1000 Hz (20 kHz)
Audio Sensitivity	130 mV nominal for 60% system deviation 25/30 kHz and Japan models 50 mV nominal for 60% system deviation 20 and 12.5 kHz models
FM Noise	50 dB (45 dB @12.5 kHz EIA)
Audio Response	+1/-3 dB from 300 to 3000 Hz +1/-1.5 dB from 400 to 2700 Hz +1/-3 dB from 300 to 2250 Hz (12.5 kHz models) +1/-3 dB from 300 to 3000 Hz (Japan models)
Audio Distortion	Less than 3% at 1000 Hz at 60% deviation
Frequency Separation	26 or 28 MHz

RECEIVER

Audio Output	EIA: 5 Watts @3% distortion CEPT: 3 Watts @10% distortion
Input Impedance	50 Ohms
EIA Modulation Acceptance	± 7 kHz @30/25 kHz channel spacing ± 6 kHz @20 kHz channel spacing ± 4.5 kHz @12.5 kHz channel spacing
Frequency Stability	EMA Series: $\pm 0.001\%$ from -25°C to $+60^{\circ}$ ambient (+ 25°C reference) CUA Series: $\pm 0.0005\%$ from -30°C to $+60^{\circ}$ ambient (+ 25°C reference)
Squelch Sensitivity	Carrier Squelch: 10 dBq (fixed) PI, DPI: 6 dBq (fixed)
Maximum Frequency Separation	4 MHz or 12 MHz in two 6 MHz "windows" with wide spaced (dual) front end option
Spurious and Image Rejection	85 dB
Sensitivity	20 dB Quieting: 35 μV EIA SINAD: 28 μV
Intermodulation	30-25-20 kHz Channel Spacing: 80 dB 12.5 kHz Channel Spacing: 70 dB
Selectivity	30 kHz Channel Spacing: 90 dB EIA 25 kHz Channel Spacing: 85 dB EIA, CEPT 20 kHz Channel Spacing: 80 dB EIA, CEPT 12.5 kHz Channel Spacing: 70 dB EIA, CEPT

SPECIFICATIONS SUBJECT TO CHANGE WITHOUT NOTICE

UNIDEN FORCE AMH 350 SPECIFICATIONS

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This Equipment Meets or Exceeds the Following Specifications

GENERAL

Available Channels	2
Frequency Range	148-174 MHz
Size	7.32" x 10.35" x 2.1" (186 mm x 263 mm x 62 mm)
Weight	5 lbs (2.3 kg)
Power Source	13.6 VDC (NEG GND ONLY)
Transmitter	7 A
Receiver	500 mA
Frequency Control	PLL
Operating Temperature Range	-30° to +60°C
Channel Spacing	30 KHz
FCC Type Acceptance & Certification	Parts 21, 90, 15
Microphone Type	500 ohm dynamic

TRANSMITTER

RF Power Output	35 W
Modulation	16 F3
Audio Distortion	3%
FM Hum and Noise	50 dB
Spurious and Harmonic Suppression	60 dB
Frequency Stability	± .0005%
Transmitter Bandwidth	
No Degradation	2 MHz
3 dB Degradation	5 MHz

RECEIVER

Sensitivity	
(20 dB Quieting)	0.5 μ V
(12 dB SINAD)	0.35 μ V
Selectivity	
Adjacent Channel	75 dB
Intermodulation Rejection	75 dB
Spurious and Image Rejection	85 dB
Modulation Acceptance Bandwidth	7 KHz
Audio Output	
(@ 10% distortion)	5 W
Frequency Stability	± .0005%
Receiver Bandwidth	
No Degradation	± 1 MHz
3 dB Degradation	± 2.5 MHz

ICOM IC-251 A/E ALL MODE TRANSCEIVER (1/2)

SECTION 1 SPECIFICATIONS

GENERAL

Numbers of semi-conductors	: Transistor	99
	FET	12
	IC	36 (IC-251A : 35)
	Diode	133 (IC-251A : 132)
Frequency coverage	: 144.0000 ~ 145.9999MHz	
	(IC-251A : 143.8000 ~ 148.1999MHz)	
Frequency resolution	: SSB 100Hz steps FM 5KHz steps	
	1KHz steps with TS button depressed	
Frequency Control	: Microcomputer based 100Hz step Digital PLL synthesizer.	
	Independent Transmit-Receive Frequency Capability.	
Frequency Readout	: 7 digit Luminescent display 100Hz readout.	
Frequency stability	: Within ± 1.5 KHz	
Memory channels	: 3 channels, any inband frequency programmable	
Usable conditions	: Temperature: $-10^{\circ}\text{C} \sim 60^{\circ}\text{C}$ ($14^{\circ}\text{F} \sim 140^{\circ}\text{F}$)	
	Operationable time: Continuous	
Antenna impedance	: 50 ohms unbalanced	
Power supply requirement	: 13.8V DC $\pm 15\%$ (negative ground) 3A Max. or 117V/240V	
	AC $\pm 10\%$	
Current drain (at 13.8V DC)	: Transmitting	
	SSB (PEP 10W)	Approx. 2.3A
	CW, FM (10W)	Approx. 2.3A
	FM (1W)	Approx. 1.0A
	Receiving	
	At max. audio output	Approx. 0.6A
	Squelched	Approx. 0.4A
Dimensions	: 111mm (H) x 241mm (W) x 264mm (D)	
Weight	: Approx. 5.0 Kgs	

TRANSMITTER

Output power	: SSB	10W (PEP)
	CW	10W
	FM	1 ~ 10W (Adjustable)
Emission mode	: SSB (A3J, USB/LSB), CW (A1), FM (F3)	
Modulation system	: SSB	Balanced modulation
	FM	Variable reactance frequency modulation
Max. frequency deviation	: ± 5 KHz	
Spurious emission	: More than 60dB below peak power output	
Carrier Suppression	: More than 40dB below peak power output	
Unwanted Sideband	: More than 40dB down at 1000Hz AF input	
Microphone	: 1.3K ohm dynamic microphone with built-in preamplifier	
	and push-to-talk switch.	
Operating mode	: Simplex, Duplex	
	(Any inband frequency separation programmable)	
Tone Burst	: 1750Hz ± 0.1 Hz (IC-251A : Not installed)	

ICOM IC-251 A/E ALL MODE TRANSCEIVER (2/2)

RECEIVER

Receiving system	: SSB, CW Single conversion superheterodyne FM Double conversion superheterodyne
Receiving Mode	: SSB (A3J, USB/LSB), CW (A1), FM (F3)
Intermediate Frequency	: SSB, CW 10.7MHz FM 10.7MHz, 455KHz
Sensitivity	: SSB, CW Less than 0.5 microvolts for 10dB S+N/N FM More than 30dB S+N+D/N+D at 1 microvolt Less than 0.6 microvolts for 20dB Noise quieting
Squelch sensitivity	: SSB, CW Less than 0.6 microvolts FM Less than 0.4 microvolts
Spurious response rejection ratio	: More than 60dB
Selectivity	: SSB, CW More than ± 1.2 KHz at -6dB point Less than ± 2.4 KHz at -60dB point FM More than ± 7.5 KHz at -6dB point Less than ± 15 KHz at -60dB point
Audio output power	: More than 1.5W
Audio output impedance	: 8 ohms

SIDEBAND TECHNOLOGY ACSE PIONEER 1000

Performance Specifications for the Sideband Technology ACSE' POINEER 1000 VHF Narrowband Mobile Radio

GENERAL

Dimensions	9½" W x 2½" H x 11" D (241 x 67 x 280 mm)
Weight	5 lbs. (2.27 kg)
Power Requirements	
Voltage	13.6 VDC + 20% Negative Ground
Current Drain	
Receive (Squelched)	400 ma
Receive (Max Audio Output)	1.5 A
Transmit (Avg. Speech)	3 A
Transmit (Peak)	7 A
Microphone	Heavy Duty Dynamic
Antenna Switching	Solid State - Pin Diode
Power Switching	Solid State
Frequency Range	150-174 MHz
Channels	4 Simplex, 2 Dual Frequency Simplex and 2 Talkaround
	Tone Coded Squelch Optional

TRANSMITTER

Power Output	25 Watts PEP (Peak Envelope Power)
Frequency Stability	4 PPM Standard, 2 PPM Options ¹ -30° to +60° C
Modulation	3A3J with 3 kHz Identity Carrier
Audio Response	+1, -3 db, 300-2500 Hz
Modulation Distortion	Less Than 3%
Spurious/Harmonic Output	60 db Below PEP
Hum and Noise	-40 db
Channel Frequency Spread	5 mHz

RECEIVER

Sensitivity	.3 uv for 10 db S+N/N .2 uv for 20 db quieting
Selectivity	60 db @ 5 kHz Channel Spacing 80 db @ 25 kHz Spacing
Intermodulation Distortion	75 db
Spurious/Image Rejection	85 db
Frequency Stability	4 PPM Standard, 2 PPM Optional -30° to +60° C
Audio Power Output	10 Watts @ 5% Distortion
Channel Frequency Spread	5 mHz

APPENDIX B

NARROWBAND versus WIDEBAND FM

Using the definition of Taub and Schilling [74]⁷, one can draw the line on what is called a narrowband or a wideband FM system:

"In studying the signal to noise ratios of FM systems, one realizes that the FM systems allow us to sacrifice bandwidth for the sake of improving signal to noise ratio. The improvement begins to make itself apparent when the modulation index β is over 0.5 or 0.6. This value of β is roughly the value which establishes the demarcation between "narrowband" and "wideband" FM. Thus, signal to noise improvement is a feature of wideband FM and is not shared by narrowband FM".

The FM modulation index β is defined as:

$$\beta = \frac{\Delta f}{f_m} = \frac{\text{frequency deviation}}{(\text{highest}) \text{ modulating frequency}}, \quad (1.1)$$

Consequently, the FM systems used in this study can be considered as wideband FM, as their modulation index for voice and for a 1 kHz tone modulating signal is well over the minimum 0.5 limit stated above:

$$\begin{aligned} \beta_{\text{voice}} &= \frac{5 \text{ kHz}}{3 \text{ kHz}} = 1.67, \\ \beta_{1 \text{ kHz}} &= \frac{5 \text{ kHz}}{1 \text{ kHz}} = 5, \end{aligned} \quad (1.2)$$

and therefore should show a signal to noise improvement above the threshold level.

Other authors [93] [141] define narrowband FM as having a small modulation index (i.e., $\beta \ll 1$) and wideband FM as having a large one, without indicating a specific demarcation value. Finally some authors [142] define the 5 kHz deviation standard used in the land mobile as narrowband.

⁷ Note that the references of the Appendices are located in the previous References section.

APPENDIX C

PEP and TOTAL AVERAGE POWER DERIVED from the AVERAGE POWER of 2 FREQUENCY COMPONENTS

C.1 PEP DERIVED FROM THE AVERAGE POWER OF TWO FREQUENCY COMPONENTS

In order to calculate the PEP for linear modulation schemes from the average power of the frequency components seen on the spectrum analyser, one has to observe that what is given on the spectrum analyser is the average power (in dBm) of each frequency component of the voltage spectrum. The total average power can be found as the sum of all these components. The same way, the Peak Envelope Power (PEP) can be found as the sum squared of these components:

$$P_{ave} = \frac{V_{1rms}^2}{R} + \frac{V_{2rms}^2}{R} + \frac{V_{3rms}^2}{R} + \dots = P_{1ave} + P_{2ave} + P_{3ave} + \dots$$

$$PEP = \frac{(V_{1rms} + V_{2rms} + V_{3rms} + \dots)^2}{R}$$

Also, using: $\text{dBm} = 10 \log_{10}(P/1 \text{ mw})$ or $P = .001 \text{ antilog}_{10}(\text{dBm}/10)$ and $P = V_{rms}^2/R$, with $R = 50 \Omega$, one finds the RMS Voltage directly as:

$$V_{rms} = \sqrt{0.05 \text{ antilog}_{10} \left(\frac{\text{dBm}}{10} \right)}$$

Taking figure 3.12 as an example, one can neglect the low power components, since their contributions to the PEP is very small. Only the two strong components (42 and 30 dBm) of the modulated pilot and modulated 1 kHz tone can be used for the calculation:

$$42 \text{ dBm} \rightarrow 28.15 \text{ V}_{rms} \rightarrow 15.85 \text{ Watts average,}$$

$$30 \text{ dBm} \rightarrow 7.07 \text{ V}_{rms} \rightarrow 1.00 \text{ Watt average,}$$

for a total of 16.85 watts average (42.27 dBm); and the PEP is:

$$PEP = \frac{(28.15 + 7.07)^2}{50} = 24.8 \text{ Watts} = 43.9 \text{ dBm.}$$

The same results can be obtained if one prefers to work with the maximum voltages instead of with the RMS voltages:

$$P_{ave} = \frac{V_1^2}{2R} + \frac{V_2^2}{2R} + \frac{V_3^2}{2R} + \dots = P_{1ave} + P_{2ave} + P_{3ave} + \dots$$

$$PEP = \frac{(V_1 + V_2 + V_3 + \dots)^2}{2R}$$

$$V = \sqrt{0.1 \text{ antilog}_{10} \left(\frac{\text{dBm}}{10} \right)}$$

$$42 \text{ dBm} \rightarrow 39.81 V_{max} \rightarrow 15.85 \text{ Watts average,}$$

$$30 \text{ dBm} \rightarrow 10.00 V_{max} \rightarrow 1.00 \text{ Watt average,}$$

$$PEP = \frac{(39.81 + 10.0)^2}{100} = 24.8 \text{ Watts} = 43.9 \text{ dBm.}$$

Independently of the method used, one sees that in this case, where the two frequency components are 12 dB apart, the PEP (in dBm) is given by the average power (in dBm) of the stronger component plus 1.9 dB.

More generally, this value could be found independently of the power of the 2 individual components, for various dB separations between them. Let δ be the difference in dBm between the two components and Δ the difference in dB between the PEP and the average power of the stronger component. Given δ , one wants to find Δ . We have:

$$\begin{aligned} \delta &= 10 \log \left(\frac{P_1}{1 \text{ mw}} \right) - 10 \log \left(\frac{P_2}{1 \text{ mw}} \right) \\ &= 10 \log \left[\frac{(V_1^2/2R)}{1 \text{ mw}} \right] / \left[\frac{(V_2^2/2R)}{1 \text{ mw}} \right] \\ &= 10 \log \frac{V_1^2}{V_2^2} = 10 \log \left(\frac{V_1}{V_2} \right)^2 \end{aligned} \quad (1)$$

and:

$$\begin{aligned} \Delta &= 10 \log \left(\frac{PEP}{1 \text{ mw}} \right) - 10 \log \left(\frac{P_1}{1 \text{ mw}} \right) \\ &= 10 \log \left[\frac{(V_1 + V_2)^2/2R}{1 \text{ mw}} \right] / \left[\frac{V_1^2/2R}{1 \text{ mw}} \right] \\ &= 10 \log \frac{V_1^2 + 2V_1V_2 + V_2^2}{V_1^2} \end{aligned} \quad (2)$$

Then, from (1) and (2):

$$\frac{V_1^2}{V_2^2} = \text{antilog}(0.1 \delta) \quad (3)$$

and

$$\frac{V_1^2 + 2V_1V_2 + V_2^2}{V_1^2} = 1 + \frac{2V_2}{V_1} + \frac{V_2^2}{V_1^2} = \text{antilog}(0.1\Delta) \quad (4)$$

Substituting (3) into (4), and isolating Δ :

$$\Delta = 10 \log \left[1 + \frac{2}{\sqrt{\text{antilog}(0.1\delta)}} + \frac{1}{\text{antilog}(0.1\delta)} \right]$$

so, for example, for $\delta = 12$ dB, $\Delta = 1.9$ dB, and for $\delta = 0$ dB, the PEP (in dBm) will be $\Delta = 6$ dB above the average power value (in dBm) of the 2 equal frequency components shown on the spectrum analyser.

In general, values of PEP (in dBm) for a two frequency situation can be found by adding Δ dB (as calculated above) to the strongest component (in dBm) as seen on the spectrum analyser.

C.2 TOTAL AVERAGE POWER DERIVED FROM THE AVERAGE POWER OF TWO FREQUENCY COMPONENTS

The same way, the total average power could be found from the average power of two frequency components. As seen above, for 2 frequency components of 42 and 30 dBm, the total average power of the waveform was of 42.27 dBm, or 0.27 dB above the value of the stronger component.

Again, this value could be found independently of the power of the 2 individual components, for various dB separations between them. Once more, let δ be the difference in dBm between the two components and Υ the difference in dB between the total average power and the average power of the stronger component. Given δ , one wants to find Υ . We have:

$$\begin{aligned} \Upsilon &= 10 \log \left(\frac{P_1 + P_2}{1 \text{ mw}} \right) - 10 \log \left(\frac{P_1}{1 \text{ mw}} \right) \\ &= 10 \log \frac{V_1^2 + V_2^2}{V_1^2} \end{aligned} \quad (5)$$

and:

$$\begin{aligned} \delta &= 10 \log \left(\frac{P_1}{1 \text{ mw}} \right) - 10 \log \left(\frac{P_2}{1 \text{ mw}} \right) \\ &= 10 \log \frac{V_1^2}{V_2^2} \end{aligned} \quad (6)$$

Then, from (5) and (6):

$$\frac{V_1^2}{V_2^2} = \text{antilog}(0.1\delta) \quad (7)$$

and

$$\frac{V_1^2 + V_2^2}{V_1^2} = 1 + \frac{V_2^2}{V_1^2} = \text{antilog}(0.1\Upsilon) \quad (8)$$

Substituting (7) into (8), and isolating Υ :

$$\Upsilon = 10 \log \left[1 + \frac{1}{\text{antilog}(0.1\delta)} \right]$$

So that in general, values of total average power (in dBm) for a two frequency situation can be found by adding Υ dB (as calculated above) to the strongest component (in dBm) as seen on the spectrum analyser.

APPENDIX D

OVERVIEW of the PROBLEMS TRADITIONALLY ASSOCIATED with SSB, and SUMMARY of the RECENT PILOT-BASED SSB RESEARCH

In this Appendix, the problems traditionally associated with SSB are described, and a summary of the recent research involved in finding a solution to these problems is presented.

D.1 PROBLEMS OF VHF SSB

Among the currently available analog modes of modulation, single sideband yields the best ratio between transmitted RF (radio frequency) bandwidth and baseband bandwidth. For example, the transmission of the usual 3 kHz baseband speech signal requires about 15 kHz of RF bandwidth for FM (Carson's rule, see footnote⁸), 6 kHz for AM (theoretically about twice the baseband bandwidth), and 3 kHz for SSB or ACSSB (theoretically about equal to the baseband bandwidth). The theoretical bandwidth of each modulation scheme is shown in figure D.1 within an idealized channel spacing assignment.

In view of the narrowband advantage, it is reasonable to ask why SSB was not adopted before in the civil land mobile VHF radio service. There are a number of problems that have traditionally made FM more advantageous than SSB in the land mobile bands. A more detailed description of some of these problems will help in analyzing the solutions proposed subsequently.

⁸ In textbooks on modulation theory (e.g., [74]), Carson's rule is used to determine the theoretical FM bandwidth. This rule states that: "the bandwidth is twice the sum of the maximum frequency deviation and the modulating frequency". Expressed mathematically this is:

$$B = 2(\Delta f + f_m)$$

where B is the bandwidth, Δf is the frequency deviation, and f_m is the highest modulating frequency. In the case of a 1 kHz modulating tone with a 4.5 kHz deviation, $B = 11 \text{ kHz}$; for voice modulation, $f_m = 3 \text{ kHz}$ and $B = 15 \text{ kHz}$.

D.1.1 Carrier reinsertion at the receiver for acceptable speech quality and intelligibility (frequency offset problem)

Single Sideband techniques were developed prior to World War II. Because of its channel efficiency, SSB has been used for almost all speech channels in the High Frequency (HF) band (3–30 MHz) for many years. The type used at HF is suppressed carrier SSB (emission designator: A3J) where only a single modulation sideband is transmitted (see figures D.1 and D.2–A). With suppressed carrier SSB systems, the carrier component used for product demodulation is generated in the receiver and may therefore slightly differ in frequency from the true carrier frequency value. This small frequency offset appears as an equal frequency translation (either up or down) in each Fourier component of the receiver audio output, with consequent loss of naturalness of speech (sometimes referred to, by SSB radio operator, as the “Donald Duck” effect), and even loss of intelligibility if the offset is large. While it is true that speech remains reasonably intelligible with offsets up to ± 150 Hz, the naturalness is affected for offsets exceeding ± 50 Hz. Speaker recognition may also be impaired. Thus for speech transmission an offset not exceeding ± 25 Hz appears a reasonable goal. For some applications, e.g. sub-audio tone muting, where tones are selected by narrow bandpass filters, even greater frequency accuracy is essential. By contrast, the frequency stability of a crystal oscillator in a land mobile equipment is usually taken as ± 5 parts in 10^6 . This results in an acceptable ± 50 Hz frequency stability at 10 MHz, but in an unacceptable one of ± 500 Hz at 100 MHz. Most future equipments will be synthesized and a better temperature compensated crystal oscillator (TCXO) may be used as the standard (since only one will be required). Even so, the cost of such oscillators climbs rapidly if better than ± 1 part in 10^6 (± 100 Hz at 100 MHz) stability is specified. This level of stability has been used in the Yugoslavian VHF SSB systems, utilizing TCXOs, and has been said to provide reliable SSB communications below 100 MHz [56]⁹. But for higher RF frequencies, more stability is required. The all-digital temperature-compensated oscillator may yield a breakthrough here [27], if the cost of its commercialized version can be kept low.

This relatively low frequency stability of economical crystal oscillators for land mobile equipment is one of the main reason that made suppressed carrier SSB uneconomically suitable for VHF and UHF frequencies.

⁹ Note that the references of the Appendices are located in the previous References section.

FIGURE D.1 : ANALOG MODULATION SPECTRAL ANALYSIS

FIGURE D.2 : VARIOUS SINGLE
SIDE-BAND TRANS-
MISSIONS

D.1.2 Operation of the Automatic Gain Control in the fading environment

Like all AM systems, SSB requires good automatic gain control (AGC) to overcome signal fading. In the mobile environment, *"fade rates (at VHF) as high as 1000 dB/second are sometimes encountered and fade depths in excess of 30 dB are common, thus good AGC is particularly important"* [29]. AM systems have a constant amplitude reference in the carrier component, thus AGC is designed to monitor the carrier level and keep it constant, as far as possible. Well designed, it yields nearly constant audio output levels.

Suppressed carrier SSB can not operate in the same way. If the AGC voltage is simply derived from the mean signal amplitude (as with AM) it tends to compress the audio signal but, worse, gives maximum receiver gain in between words, when the received signal vanishes. The audible effect is to fill the inter-word gaps with loud receiver noise and is very annoying for operators. Co-channel interference, even at a low level, is also emphasized by the gain increase between words. In HF practice, the effect is overcome by using "hang" AGC in which the gain is held at a low level for a fixed time interval after the signal disappears. This is not suitable for use at VHF, where fading is much more rapid, and this technique also behaves unsatisfactory in the presence of impulsive noise.

D.1.3 Sensitivity of narrow-band systems to impulsive noise

The predominant type of noise in the land mobile environment is not white but impulsive, derived principally from ignition systems of petrol engines. The effect of impulsive noise on SSB at VHF is a matter of considerable interest. It has been claimed that the effect on SSB is more severe [75] than for AM, FM, and NBFM (Narrowband FM) systems, to the extent that SSB might be considered hardly usable. Certainly if "hang" AGC is used, this will be so, since each impulse will trigger the receiver into low gain for a fixed, quite long, interval. However, other authors report impulsive noise as being little different in its effect from that of 12.5 kHz AM and NBFM systems. Some experiments [28] confirm that impulsive noise would not present a more severe problem with SSB than with other narrowband modulation systems, and that the utilization of clippers or blankers in the receiver would give a worthwhile improvement, as in AM systems.

D.1.4 High level of spurious and out-of-band radiation from SSB transmitters

The SSB transmitters used at HF generate the SSB signal at low level, with linear amplification up to the transmitted power level. Such transmitters have many disadvantages. They

are relatively inefficient in conversion of DC to RF: figures as low as 15% are not uncommon. Noise from the low level stages is also amplified by the linear amplifier; moreover, non-linearities in the amplifier result in substantial spurious emission - mainly odd order intermodulation products - from the transmitter, typically as little as 30 dB below the maximum power of the wanted signal. Although it has been claimed that mobile AM and FM transmitters give rise to equal or worse spurious adjacent channel emission in a 6.25 kHz channeling [76], a substantial improvement in SSB transmitter performance, both in respect of better power efficiency and lower spurious emission, would greatly enhance the possibility of a VHF SSB land mobile radio system.

D.1.5 Expense and complexity of SSB equipment in relation to FM

One of the major constraint associated with all the narrowband techniques in the UHF and VHF land mobile environment is the cost due to temperature/stability requirement of the crystal oscillators. Additional costs for SSB systems are due to the automatic gain control extra circuits needed to enable the receiver to overcome rapid and deep signal fading, and to good linear power amplifiers.

D.2 PILOT-BASED SSB SCHEMES

As will be demonstrated through an overview of the recent research related to SSB usage in the UHF and VHF bands, the above problems are said to have been solved, for example, by transmitting a pilot reference signal along with the audio signal, and by submitting the audio to various forms of signal processing such as amplitude companding and pre-emphasis. The pilot provides a reference for an Automatic Frequency Control (AFC) that corrects the frequency offset, and is also used for Automatic Gain Control (AGC). The signal processing improves the audio quality and resistance to noise, and is also used to shape the emitted spectrum and reduce the spurious emissions. Implementation is cost effective because of today's availability of high level of circuit integration.

The pilot signal can take several forms. Examples are: pilot carrier (figure D.2-B), in-band pilot tone (figure D.2-C), transparent tone-in-band pilot (figure D.2-G), above band pilot tone (figure D.2-D), or a complex audio sub-carrier containing control information (figure D.2-E) as in the case of systems such as Lincompex and Syncompex [47] [50-55] [77-84], and as in the case of the experimental Amplitude Companded Single Sideband (ACSB):

figure D.2-F). The use of a pilot spread over the audio bandwidth is also being investigated by some groups [1] [85].

These systems may generally be categorized as pilot SSB. Some authors have estimated the various forms of pilot SSB as having roughly similar performances [70] [86].

D.2.1 Pilot Carrier SSB

Research by Wells [24-26] at the Philips Research Laboratories was done using a pilot carrier SSB system (without amplitude companding) at 85 MHz. The results of field trials done on voice and data transmission at VHF frequencies are reported. For comparison, the SSB transceivers were extensively field tested against "top of the range" AM and FM systems at 12.5 kHz and FM systems at 25 kHz. In conclusion to his work, Wells mentioned that:

"Under strong signal conditions the audio quality of the SSB equipment is excellent and compares well with the 25 kHz FM unit. Under fairly weak signals the SSB unit remains comparable but the effects of signal fading sound markedly different. The SSB receiver shows an amplitude flutter on its output and the FM receiver shows loud noise burst. The effect of impulse noise are equally disturbing on both units but again sound very different."

The SSB radios have excellent performance under quasi-synchronous operation; easily out performing the FM units. There were no significant microphonic effects from the frequency synthesizer; its operation was entirely satisfactory.

Ten SSB units have been in operation for more than 1 year. They have not required frequency adjustment and their few faults were typical of normal AM and FM equipment."

Moreover, his work showed that in heavy traffic, in an urban environment, a narrow channel VHF SSB radio performs at least as well as current 12.5 kHz AM and FM equipments, that the SSB radios were less susceptible to ignition interference than the wider channel equipments, and that the automatic gain control worked well at frequency up to 200 MHz. He also concluded that operation at UHF would be possible using feedforward AGC.

D.2.2 Above-Band Pilot SSB

An experimental pilot SSB system using amplitude companding and pre-emphasis with a modulated above-band pilot scheme was developed at Stanford University as a result of an FCC supported study undertaken to determine whether the existing mobile radio bands could be used more effectively in order to allow more traffic in the VHF and UHF bands [6-18]. Their system was given the name "Amplitude Compandored Single Sideband" or "ACSB".

The research program had three major objectives: to identify the most spectrum-efficient technology for mobile radio, to demonstrate the feasibility of that technique in operating conditions, and to encourage industry to adopt the technology.

Identifying the most spectrum-efficient technology began with the first study [8]. An analytical review showed that pilot SSB employing both amplitude and frequency compression was best from the point of view of frequency usage. Pilot SSB employing amplitude companding only (ACSB) a close second. Amplitude Companded FM was a distant third and conventional FM an even more distant fourth. Other techniques such as Continuously Variable Slope Delta Modulation (CVSDM), and digital voice synthesis such as Linear Predictive Coding (LPC) were also considered but dismissed for reasons of poor spectrum efficiency, sensitivity to background noise, voice quality, implementation costs, etc.

The second phase of the work thus concentrated on pilot SSB systems with amplitude companding (ACSB), and on ACSB with frequency companding. Radios of both types were developed and carried through prototype design, bench and field tests. Although the frequency compression systems [87-88] (based on voiced/unvoiced decision) generally yielded better performance in terms of spectrum efficiency, it was abandoned in mid-'79 because of the higher cost associated with the analog implementation of their design, and the lower voice quality (specially for female voices) produced by the reduction in bandwidth. Subsequent research was concentrated on pilot SSB with amplitude companding (ACSB) without any frequency companding.

Amplitude companders work by reducing the amplitude of loud syllables and increasing the amplitude of quiet passages to achieve a transmitted signal more even (compressed) in power level (see figure D.3). After transmission and reception, the signal is restored (expanded) to its original form (compressor plus expander equals "compander"). The result is that noise occurring during quiet passages is greatly reduced; noise during loud passages is increased, but it is masked by the loudness of the passage itself.

In one of the earlier reports [14], Lusignan describes the subjective improvement of ACSB, over SSB, due to amplitude companding, pilot pumping, and pre emphasis:

"In normal SSB, the signal to noise ratio is equal to the carrier to noise ratio. In the ACSB radios developed and tested in the research, three modifications are made to improve the signal to noise performance for voice signals:

- 1- Amplitude companding offers an improvement of 6 or 7 dB at marginal signal levels, over 15 dB at good signal levels,*

AMPLITUDE COMPANDING

FIGURE D.3 : 4:1 COMPANDOR/EXPANDOR SYSTEM

- 2- Amplitude pumping (a second stage of amplitude companding) adds another 6 to 7 dB, and
- 3- Pre-emphasis adds another 3 or 4 dB.

Whereas normal SSB radios require about 22 dB carrier to noise for an intelligible signal, the ACSB radios gave an acceptable signal at about 5 or 6 dB, carrier to noise."

In the final report [6], the advantage of using a pilot is summarized:

"In ACSB radios, the frequency and gain problems are eliminated by the use of a pilot signal that is transmitted along with the voice at a frequency just above the voice band. This signal is used in the receiver to provide the reference for an automatic frequency control (AFC) and automatic gain control (AGC) circuit".

Note also that in these experimental prototypes, the pilot is frequency modulated (a 40 Hz tone was used to modulate the pilot) to help avoid capture by coherent interferers. On the receiver side, the modulated pilot provides the tone detection which opens the audio squelch only when the correct signal is present; the spectrum is scanned over a range of ± 800 Hz, and the automatic frequency control circuits lock to the carrier which carries the correct FM frequency on its pilot. This pilot is also used for automatic gain control, and corrects for fading rates up to 20 Hz.

The use of companding is said to solve the noise problem and produce a "capture effect" similar to the one of FM [7]:

"Another disadvantage with SSB radios is that in most applications they are noisier than FM radios. In FM the noise level in the radio receiver is reduced by the action of the FM detector circuits. In SSB the noise level that is heard at the speaker is the same as that received by the radio receiver; there is no quieting of the noise in SSB equivalent to the FM improvement. The noise problem in ACSB radios is solved by the use of companders.

This compander improvement is similar to the FM improvement or "capture effect". The compander improvement or "capture effect" works as well for co-channel or adjacent channel interference as it does for random noise".

The problem of spurious emission due to non-linearities of the linear amplifier is also considered as solved by the use of "pilot pumping" and pre-emphasis:

"Normal SSB radios also have difficulty controlling spreading of the transmitted signals due to non-linearities in the radio amplifier. In the ACSB radio, this intermodulation spreading is controlled by shaping of the voice spectrum (pre-emphasis) and by reducing the transmitted pilot level during loud syllables (pumping). These controls reduce the level of interference that is spread to adjacent radio channels. Restoring the natural spectrum in the receiver (de-emphasis) also improves the signal to noise ratio. Varying the pilot level is also used in the compander circuit of the receiver to recover the audio signal; this allows a greater compander improvement to be achieved."

The final report [6] concluded with a summary of the superiority of ACSB over FM:

"In the quality range important to mobile radio (15 dB to 30 dB signal to noise ratio) the amplitude companded SSB system provided the same or better quality reception than current FM systems with comparable transmitter power (the average SSB power is about 6 dB less than the FM power). These narrow-band systems also gave the same or better co-channel interference isolation and far better adjacent channel interference rejection... Because ACSB has a co-channel separation distance no greater than FM's, and uses only one-fifth the bandwidth (i.e., 5 kHz), a five-fold advantage can be achieved in spectrum-use efficiency over conventional FM (25 kHz) systems".

A study was also done on the multi-channel intermodulation aspect of ACSSB, and showed the feasibility of an efficient utilization and an adequate performance of multi-channel ACSSB systems [17-18].

D.2.3 In-Band Pilot Systems

Extensive research has also been done at Bath University in the U.K. with pilot SSB systems [1] [27-42]. Their experimental system has been designed to use only 5 kHz bandwidth at 70 dB adjacent channel protection. It uses in-band pilot tone and is called the Wolfson SSB system.

At the beginning of the Wolfson SSB project, a study of the system's operation principles was undertaken in an attempt to eliminate the problems commonly associated with this form of modulation. Field trials with both suppressed carrier DSB and SSB systems quickly led the team to the conclusion that no envelope derived automatic gain control system could meet the exacting requirements of the mobile radio environment. Consideration was therefore given to ways in which a constant amplitude tone could be transmitted. The authors analysed three possibilities:

- (a) pilot carrier,
- (b) pilot tone in-band, and
- (c) pilot tone in-band but spread across the audio band by direct sequence pseudo-noise spreading.

A detailed advantages and disadvantages comparison of the 3 systems is given in reference [1]. Consideration of the respective system properties led to the adoption of the in-band pilot tone.

In the system build, the pilot tone was positioned at the centre of the speech spectrum, the frequency being 1.667 kHz. In the transmitter speech processing circuits, a bandstop

filter producing a 350 Hz wide (-3 dB points) notch in the speech spectrum was centered on the tone frequency, and the tone level was then fixed at a level of -15 dB relative to the peak speech power. In the receiver, the tone was suppressed from the audio output by means of a bandstop filter, thus rendering it inaudible. Based on the studies reported in reference [89], it was concluded that the resulting "hole" in the audio frequency (AF) spectrum had negligible effect on speech intelligibility. Note also that this system did not use amplitude companding.

In the Wolfson SSB project a new transmitter (86 MHz) developed by Petrovic and Gosling was used (polar loop transmitter [30-32]). Unlike the linear transmitter, the new system used a power oscillator at channel frequency followed by two or three stages of class C power amplification. By sampling the output and down-converting, the desired control signals were used to constrain the output spectrum to the desired form. The outputs from a conventional linear and the new polar transmitter are compared in figure D.4. The improved output spectrum is immediately apparent. A 14 watt VHF transmitter operating with a -15 dB pilot, and sinusoidal modulation at a speech frequency, produced intermodulation products which fall below -70 dB at ± 2 kHz relative to the center of the band. This particular design used a VMOS output stage and had a power efficiency of 55%.

The authors conclusions [1] summarize well the performances obtained with the Wolfson SSB system:

"In comparison with commercial AM and FM equipments, the quality and performance of the in-band pilot SSB in the exacting fading and impulsive environment is impressive. The SSB receiver showed remarkable freedom from ignition interference in the VHF bands: better than either AM or FM commercial equipments. A possible explanation as to why this should be so was first put forward by Gosling [28]. It would appear that after being stretched by the SSB filter the length of the pulse is still of insufficient length to be perceived (it is estimated that the pulse would have to be some ten to fifteen times longer). Also, in perception of short pulses the total energy content is a more important factor than the normal parameters of amplitude and duration."

D.2.4 Phase-Locked Transparent tone in-Band

In an effort towards standardization, the researchers at Bath University recognized the fact that, for pilot tone SSB to be universally adopted, any system must be capable of vertical integration across the frequency bands, i.e. the system and spectrum configuration used at VHF must be those used, with minor modifications, at UHF. At this point of their research, an analysis of three pilot-based systems was done [41]:

FIGURE D.4 : COMPARISON OF OUTPUT SPECTRA FROM CONVENTIONAL
& POLAR-LOOP SSB TRANSMITTER

"At VHF, no one system has clearly emerged as the system to use. However, it is generally accepted that Tone in-Band (TIB) is the most radical approach, or so it would appear, since a part of the audio spectrum is removed from the central region of the audio band by a notch filter for the tone to be inserted. In doing so, the original aim at Bath University of achieving the most spectrum efficient speech system is satisfied together with a system which offers the greatest degree of adjacent channel protection, a good correlation between fades on the pilot tone and fades on the audio signal and finally, a large symmetrical pull-in range for the frequency control circuitry to operate. These three points were felt to be particularly important if SSB were to be eventually extended in its VHF form to the higher frequency bands. Although tone in-band SSB has proven entirely satisfactory for speech, and data (provided the tone position is carefully selected) the system, it must be admitted, has not received universal acceptance through its non-transparency with all data systems.

In this respect, Tone Above-Band (TAB) and pilot carrier SSB have a definite advantage. However, for each of these two systems, transparency is achieved at the expense of placing the reference pilot to one side of the audio spectrum, thus rendering the tone more vulnerable to adjacent channel interference and requiring an asymmetric pull-in behaviour from the automatic frequency control circuitry. Furthermore, unless frequency off-setting techniques are employed [90], the pilot tone for each of these two systems will be positioned in a region of high differential group delay with respect to the majority of the audio band attributable to the IF crystal filter, and this can degrade the performance of the AGC and AFC systems".

After extensive analysis, the authors concluded that the best system design would require the advantage of the TIB but without the problem of non-transparency [37]:

"Because less flexibility is offered by the pilot carrier scheme or by the TAB systems, the specified requirements for an ideal system in relation to adjacent channel protection, symmetrical pull-in range and good pilot tone/signal correlation with fading, have been solved with the development of an improved configuration called phase-locked transparent tone in-band (TTIB)".

Moreover, to counteract the transmitter and receiver oscillator drifts, and the rapid random amplitude and phase fluctuation superimposed on the received signal by multipath propagation, a feedforward automatic gain and frequency control was adopted [36] [38-39]. In its first form, a simple modification to the TTIB processing allowed data, coherent and non-coherent, to be transmitted in the fading environment. In its second form, a combined TTIB/FFSR (Transparent Tone In-Band/Feed Forward Signal Regeneration) system is used to transmit and receive both speech and data at frequencies up to 900 MHz in the mobile radio band [37]:

"By using these 2 techniques, researchers at the University of Bath have claimed complete success in the transmission of speech and data over land mobile radio links subject to severe multipath propagation effects. The tests have included transmission of coherent

data formats such as Differential Phase Shift keying (DPSK) and Coherent Phase Shift Keying (CPSK) over a 900 MHz fading channel".

D.2.5 Pilot SSB With and Without Amplitude Companding

McGeehan and Bateman from Bath University have also compared SSB with and without amplitude companding [35]. Laboratory and field tests showed that the use of amplitude companding significantly improves the subjective performance, particularly at low signal strengths. A system similar to the one proposed by Lusignan, which employs two stages of compression and subsequent expansion was applied to the Wolfson 86 MHz tone in-band SSB system. The authors concluded that [35]:

"The subjective tests show that, for an SSB system with reference tone, the improvement due to companding is of the order of 7 dB at low signal strength and about 11 dB at high signal strengths. Although these relative improvements are somewhat lower than those indicated by Lusignan they nonetheless provide a significant increase in intelligibility at low signal levels".

They also found that by using amplitude companding, the disturbing effect of ignition noise between words was greatly reduced by the expander action in the receiver.

Another conclusion reached in their study is that although, in theory, the higher the companding ratio used the greater the improvement in S/N at the receiver output, in practice, limitations in the transmitter and receiver performance restrict the order of companding permissible.

D.2.6 Pilot Carrier, Tone In-Band, or Tone Above-Band Pilot

McGeehan and Gosling [29] have used an in-band pilot tone at roughly the center of the RF spectrum, while Wells [24] has used a partially suppressed carrier, and Lusignan [9] has used a frequency modulated tone above the audio band. In order to evaluate which of the three schemes was giving the best performance, Garner and Gibson of Philips Research Laboratories (U.K.) designed and tested phase locked loop SSB receivers for the three types of pilot scheme (pilot carrier, tone in-band, tone above-band). Their paper [86] thoroughly describes the advantages and disadvantages of each pilot scheme. The results of their tests showed that pilot carrier, tone in-band, and tone above-band systems give very comparable results with speech modulation. They also showed that tone in-band had some advantages, such as better adjacent channel performance and less variation in relative delay between

the pilot and the speech signal, but had severe restrictions on data and signalling format transmissions.

D.3 FM AND SSB IN A FADING ENVIRONMENT

It is often argued that wideband FM (see Appendix B for the demarcation between narrowband and wideband FM), because it exhibits capture effect, has superior spectrum economy to SSB, which is an essentially linear system. This argument is advanced in two ways:

A (wideband) FM receiver with an input S/N ratio well above threshold will have a superior performance to that of SSB [91]. However, as the input S/N falls below the threshold value, the output S/N ratio of the receiver falls extremely rapidly. Although SSB has an apparent advantage over FM in this region, because of its linear nature, it is occasionally pointed out that the S/N ratio is too small to be of any practical use [2]. But this conclusion is achieved assuming the ideal conditions of no fast fading. In practice, the signal received by the mobile receiver will usually have no direct line-of-sight component, but will consist in a number of scattered waves. The resulting signal will suffer random amplitude and phase variations, the amplitude variations being Rayleigh distributed. An SSB signal undergoing a deep fade produces a linear degradation of the output S/N ratio, but this is unlikely to affect the intelligibility of the speech significantly, unless the fade is of long duration. With FM operating in a Rayleigh fading environment the situation is somewhat different. As soon as the received signal fades below the receiver threshold the audio output is heard to switch from signal to noise, a much more disturbing effect to the user than with the SSB case. This, therefore, implies that there is a mean signal level some 10 dB or so above the threshold value, below which an FM signal in a fading environment will suffer severe impairment [92]. This is not so for SSB, as has been shown in the research work carried out by the U.K. Philips Research Laboratories [24].

A somewhat analogous situation exists when co-channel interference is present. Towards the edge of the coverage area, where this effect tends to occur, an SSB receiver subjected to an interfering signal will deliver both signals from its output. Provided the wanted signal is greater in magnitude than the unwanted signal for most of the time, occasional fades below the interfering level will not result in a loss of message. Even when the input S/N ratios are identical, the wanted channel can be read, provided the signal has not faded below the receiver noise floor. This characteristic of SSB systems is particularly interesting when the performance of an FM receiver operating in a similar environment is examined.

As before, when the co-channel signals are within 8 to 10 dB of each other under fast fading conditions, the audio output of the receiver will switch between the wanted and unwanted signals and cause considerable distortion of the respective messages [92].

As a result, it is not surprising that some authors consider the capture effect as a disadvantage for mobile communication systems (e.g., [93]: *"The problem of the so-called 'capture effect', where the stronger interfering signal takes over or captures the receiver, will be discussed, and particular consideration will be given to the problem of FM receiver design in order to minimize this undesirable effect"*). Hence, a gradual degradation, as provided by the linear modulation schemes, can be very advantageous in the presence of interference and/or fading.

The second issue based on capture effect, put forward in support of FM, concerns the calculation of the re-use factors [75] [94]. If the ideal conditions of no signal fading are assumed, then it is possible to show that frequency re-use is possible at shorter distances with FM than SSB. If Rayleigh fading is taken into consideration the capture effect is reduced or even eliminated together with the theoretical advantage in re-use distance [33] [95-96]. In this context it is noteworthy that Jakes [97] states that although FM co-channel interference without fading could be markedly reduced by increasing the modulation index, it remains approximately constant with index, for indices greater than unity when fading is present.

D.4 DISCUSSION

Problems associated with SSB usage have been identified and solutions suggested. Improved linear amplifiers, such as the polar loop transmitter [30-31], could solve the problem of the intermodulation spread. Recent developments (e.g., [98-99]) have also lead to inexpensive ways of obtaining very good linearities in the radio power stages, and thus could provide an acceptable solution in reducing the intermodulation products. Also, SSB has been said to minimize spectrum pollution, since the emitted power at the transmitter is proportional to the level of the modulating signal. An SSB transmitter of the same power rating as an FM transmitter will radiate less than 25% on average the power put out by an FM transmitter during speech (the average SSB power is about 6 dB less than the average FM power [100-101]). Moreover, if one considers the case of pilot SSB, during silences, the SSB system will transmit only the pilot: less than a watt or two of power.

Frequency and gain problems have been solved by the use of a pilot signal that provide (in the receiver) a reference for AFC and AGC circuits. Many other techniques such

as those developed for the Syncompex systems [47], or techniques like the speech envelope normalization [102],¹⁰ and adaptive speech companding [103], the inversion of the audio signal [18], the switched tone concept [104], improved phase locked transparent tone in-band [105], all digital temperature-compensated oscillators [27], and other schemes using digital signal processing (e.g., [58] [85] [106]) along with very high speed processing developments [107] have been suggested individually or in combination with the others to generally achieve narrower bandwidth in communication systems, and to improve the efficiency of pilot SSB in the VHF and UHF bands.

The results of the recent research look very promising: it appears that the problems traditionally associated with SSB have been solved, and that the new designs yielded systems that are highly competitive to FM in terms of costs and performance but that also have the big advantage of using only a fraction of the bandwidth used by FM.

How commercial equipment designed using some of these techniques performs can now be tested, since recently, VHF land mobile radios using SSB with above-band pilot and amplitude companding have been commercially produced in the U.S.

For example, ACSSB equipment produced by Sideband Technology Inc. (STI) has a design similar to the one proposed in Lusignan's "Convenience Circuit" report [13]: it uses 2 stages of amplitude companding (voice and pilot pumping), pre-emphasis, and the automatic gain control, as well as the automatic frequency control, are performed using the above-band pilot. One major design difference is that their pilot is not FM modulated, but consists of a single tone.

These ACSSB radios are the ones tested in this study, and some of their performances are compared to FM and SSB radios also designed to operate in the VHF band.

¹⁰ Speech envelope normalization is a form of signal amplitude compression that transforms dynamic speech waveform into constant envelope signals which are optimum for transmission and reception using analog radio equipment (AM, FM, SSB, etc.). The process is said to reduce dynamic range requirements, maximize speech SNR, increase intelligibility, and suppress noise.

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