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SPREAD SPECTRUM
FREQUENCY MANAGEMENT

by

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Because of the nation's increasing demand for more telecommunication capacity, there is a continuing need for more efficient ways of sharing the radio spectrum. The conventional ways of allocating the spectrum are by frequency, space, and time division. However, for systems using new technology this is inefficient. Hence, it is desirable to re-examine alternative procedures that might be necessary if the benefits of telecommunications are to be assured in the face of increased demand. Spread spectrum techniques, which are based on principles different than those currently used in spectrum allocation, seem to offer benefits for spectrum sharing and for some applications superior to those of frequency devision. This thesis provides a summary of the principles upon which spread spectrum systems have developed and the progress of frequency management involving spread spectrum systems. This analysis considers several strategies to

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accommodate spread spectrum in frequency management and its role in future spectrum sharing opportunities.

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Spread Spectrum Frequency Management

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ABSTRACT

Because of the nation's increasing demand for more telecommunication capacity, there is a continuing need for more efficient ways of sharing the radio spectrum. The conventional ways of allocating the spectrum are by frequency, space, and time division. However, for systems using new technology this is inefficient. Hence, it is desirable to re-examine alternative procedures that might be necessary if the benefits of telecommunications are to be assured in the face of increased demand. Spread spectrum techniques, which are based on principles different than those currently used in spectrum allocation, seem to offer benefits for spectrum sharing and for some applications are superior to those of frequency division. This thesis provides a summary of the principles upon which spread spectrum systems have developed and the progress of frequency management involving spread spectrum systems. This analysis considers several strategies to accommodate spread spectrum in frequency management and its role in future spectrum sharing opportunities.

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I. INTRODUCTION

A. BACKGROUND

As a result of advances in communication theory and systems technology in the last decade the use of telecommunication services has rapidly multiplied, placing new demands on the radio spectrum. This growth in the radio frequency spectrum usage has resulted in congestion, and the situation is getting steadily worse, Serious consequences await those agencies and nations which do not maintain an active, progressive program to protect their existing operations and to provide for accommodation of new planned systems. Competition for this vital spectrum resource has already reached the point where communications, navigation and surveillance systems in use today are threatened by encroachment from other spectrum users. In addition, any plans to introduce new systems will confront spectrum availability as a formidable problem.

Spectrum demands have been met traditionally by simple administrative techniques because technology has kept increasing the amount of spectrum space available and reducing necessary bandwidth. Recently, the growth of the usable spectrum has slowed while the demand placed upon it has grown exponentially. This turn of events has induced spectrum managers to consider different approaches to frequency allocation and assignment.

Therefore, all users must recognize the impossibility of obtaining all the spectrum requested and the virtual impossibility of exclusivity with, perhaps, several exceptions such as Tactical Air Navigation (TACAN). Conditions must be developed for cooperative use which goes far beyond the concepts of sharing that presently prevails. Given that a band must be used by more than one justifiable user, the problem is to determine the specific criteria which can be applied to two or more users on a mutually cooperative rather than a mutually exclusive basis for more effective use of the spectrum.

To overcome this problem the concept of spread spectrum (SS) communication systems has been advocated. Before such a measure may be seriously considered, extensive experimental data must be collected in order to confirm the theoretically predicted behavior of the new system. The experimental program must include field tests in real propagation and interference environments and which are performed side-by-side with existing services. Pending a favorable outcome, certain SS systems may be tentatively assigned one or more segments of certain bands.

One of the important aspects in applying SS techniques to telecommunication is the impact they will have on spectrum management. Spread spectrum systems differ from conventional systems in several ways that may require new approaches in spectrum management. They occupy much larger radio frequency (RF) bandwidths, many of them employ frequency hopping (FH), direct sequence (DS) and a combination of the two called hybrid techniques, and, often, they are designed to be multifunctional. Also, SS systems are sometimes operated in nets in which each net may serve hundreds of users in a relatively small geographical area. Even in cases that spread spectrum could be assigned to a band on a exclusive basis (a highly improbable assumption, in view of the present spectrum congestion), interaction with frequency division services would result at national and regional boundaries of such assignments.

B. PURPOSE

The purpose of this thesis is to provide an assessment of the frequency bands that might be used by spread spectrum systems, with explanations of the constraints due to both electromagnetic compatibility (EMC) considerations and frequency allocation regulations. Also, this thesis will provide administrative recommendations regarding the approach for accommodating SS systems in the frequency allocation structure. Finally, it will recommend general rules and procedures required to allow the utilization of these systems while simultaneously protecting authorized conventional systems to the maximum extent possible.

C. APPROACH

The thesis begins with this brief introduction and then divides Spread Spectrum Frequency Management into four basic areas. Chapter Two explores spectrum management allocation processes and problems. Chapter Three looks at spread spectrum systems with emphasis on the different techniques (FH, DS, and hybrid) and how their application affects spectrum management. Chapter Four assesses a global approach of spread spectrum effects on spectrum utilization. Finally, Chapter Five explores possible spectrum allocation alternatives using spread spectrum systems.

II. SPECTRUM MANAGEMENT

A. BACKGROUND

The electromagnetic spectrum (or more specifically the radio spectrum) represents a vital and intangible national resource. It is a limited resource, since only a small portion of the spectrum can be used for any given purpose within the bounds of present technology. Each radio operation requires a finite part of the spectrum, a channel, in the time and geographical domains. Unlike most other resources, the radio frequency spectrum is not worn out through use or misuse. However, careless or inefficient use may prevent the obtainment of maximum benefits.

Because of the intense competition for its use, the introduction of both national and international regulations would achieve maximum benefits. Therefore, it is essential that concerned agencies adequately provide spectrum support to ensure the protection and assignment of radio frequencies required by various users.

Since World War II, the use of the available spectrum has grown dramatically, and the United States is literally running out of space to accommodate future users of telecommunications. This problem is compounded by the fact that the spectrum management responsibilities are fragmented among many government and non-government agencies, committees, commissions, advisory boards and user groups. Because of this fragmentation no single agency has total administrative, engineering and information capabilities necessary to provide optimum spectrum management on a nationwide basis.

The spectrum shortages that exist and are developing are, to a great degree, due to the use of conservative frequency management practices from the past which were based on administrative convenience. Traditionally, communication systems have used frequency as a means to separate one communications channel from another. Often those decisions on the frequency to be used for different services were based on available technological developments and without adequate overall knowledge of propagation characteristics or of other important uses that might require frequency in a particular portion of the spectrum [Ref. 1: p. 330].

Within a given frequency channel, high-signal power has always been associated with communication reliability. As the demand for communication services increased, designers sought methods for narrowing transmission bandwidths to accommodate more users within the existing spectrum, while maintaining high signal power for communication reliability. This philosophy of spectrum usage is based on a particular course of development which the radio art happened to take, rather than on any fundamental physical principles. However, reducing assigned bandwidth also has obvious limitations, for the bandwidth assigned cannot continually be reduced without degrading the quality of system performance or requiring more costly equipment. These practices are only now beginning to be modified to take into account sound engineering principles that allow better spectrum utilization. Since past and present decisions were made using these conservative practices and were implemented with large equipment and installation expenditures, changes to conserve spectrum and alleviate shortages are therefore extremely costly. If nothing is done to improve these practices in the near future the present growth rate in usage will most assuredly create a crisis.

B. SPECTRUM ALLOCATION PROCESS

By international agreement, the usable radio frequency spectrum was sub-divided into a number of discrete frequency bands. Each of these bands was, in turn, allocated to (an appointment of specific parts of the spectrum to) one or more of the several recognized categories of radio services such as fixed, mobile and broadcast. This procedure of frequency division was based on the available technology where little was understood about the effects of the propagation characteristics at the different frequency levels. The history of major spectrum allocations is then a record of decisions primarily concerned with the allocation of spectrum previously unoccupied except for experimental purposes. The spectrum was allocated as it became usable due to advances in radio equipment technology. These technical changes and innovations occurring from time to time increased the amount of radio frequency spectrum because of better utilization techniques developed.

However, despite the fact that spectrum managers have been able to obtain more and more spectrum and, simultaneously, better frequency utilization with improved technology, this technological pace is still lagging behind the demand for spectrum use. It has reached a point where spectrum managers will have to rely on their background and knowledge to administer the spectrum without totally depending on technology to solve all their problems. In some cases the administrative route offers the best hope for improving this situation, but it is also the one which will be the most troublesome and the hardest to control. When something has been done the same way since the beginning, and where there is considerable investment in financial resources and experience, there is going to be heavy resentment and determined resistance to any attempt to modify the accepted way [Ref. 1: p. 334].

To achieve the desired goal of acceptance it is essential that advanced planning for the changing environment and technology be considered by the spectrum manager to avoid having to deal with these problems. Also, the propagation characteristics of electromagnetic energy are such that the planning for allocation of the radio frequency spectrum must be coordinated at the international as well as the national level. This coordination is a lengthly process which requires advanced planning to avoid possible delays and misunderstandings of the frequency use.

Effective utilization of the spectrum demands much more than an efficient machinery for assigning frequencies to users and keeping records of their use. It requires a continuing overall perspective on the advances of technology related to communications and electronics; constant awareness of the development of new needs and possibilities for the use of radio systems to aid the national security, the economy and the society; and a responsibility to view the needs and problems of society as a whole.

C. NATURE OF THE PROBLEM

Electromagnetic compatibility (EMC) is a two way street. The users of the electromagnetic environment must share the same resource and get along with each other. This was not a problem in the past when frequencies were plentiful and even exclusive use of frequencies was commonplace. The spectrum is now more crowded and performance thresholds are likely to be determined by the level of interfering signals, rather than by ambient noise. As a matter of fact, it is only when operational service ranges reach the limitations imposed by marginal interference, rather than noise, that the spectrum is considered to be used to full capacity [Ref. 2: p. 17].

This does not imply that the spectrum is necessarily being used efficiently under marginal interference conditions. It does mean that with the equipment in use and under the conditions of their use, interference defines the limit on the amount of service which can be accommodated. Thus, if we are to learn how to use the spectrum efficiently, we must learn to study and predict interference conditions accurately enough to determine when interference becomes an unacceptable threat.

1. Trends of Spectrum Management

Exclusive frequencies and block frequency allotments to user groups are luxuries spectrum managers can no longer afford [Ref. 2: p. 18]. However, the alternatives require the support of studies and models in more detail and with higher engineering precision than can be accomplished with the staffs, records and technical capabilities now available. The density of planned use of the spectrum in our dynamic and complex environment has forced multiple reuse of each frequency and has resulted in frequency assignments which admit to some potential form of inteference outside acceptable limits. As the use of the spectrum has become more dense, the need for more efficient methods of using the spectrum, based upon the same kind of controlled marginal compatibility, has become evident.

Three primary factors determine the degree of compatibility in our electromagnetic environment: the space, frequency and time density of spectrum use, the characteristics of the equipment in use, and the distribution of the available frequency resource among the users [Ref. 2: p. 17]. Any program that is designed to control EMC must be able to understand and control these three factors.

The resource we are interested in managing has the strange characteristic of being equally available everywhere, but subject to contamination at the point of use. The resource is only usable at any one place to the degree that the resource is not contaminated or, if it is contaminated, to the degree that the user can penetrate the contamination and still satisfy his requirements. The complex pattern of spectrum usage creates an environment within which each user must live and function. If a spectrum manager is assigned the responsibility of improving the utility of the electromagnetic spectrum, he must first understand the existing environment and then manipulate the future environment in such a manner as to improve spectrum usefulness.

2. Spectrum Management Problems

The present spectrum managment system does not have the authority to manipulate these factors, except within rigidly limited frequency bands, and therefore, cannot optimize spectrum utility. Further, existing agencies are not likely to get the required authority unless they have the means at hand to guarantee acceptable service levels to users already committed to spectrum occupancy, while at the same time assuring reliable service to new users. This can be accomplished only through the use of analytical means which have a degree of credibility acceptable to both the spectrum users and the lawmakers who must protect each user's commitment to spectrum use, and who, in addition, would have to sanction any basic change in the administration and management of the spectrum. Each proposed method for spectrum assignment must be developed, tested, measured, and proved to the satisfaction of all parties before it can achieve acceptance.

Additionally, international allocation provisions usually lag national allocations and experimentation. It is difficult to demonstrate, in advance of proof of need, that a new radio service or technique will be successful and to persuade a majority of the International Telecommunication Union (ITU) member countries to agree to the changes. Especially when this may require them to adjust existing operations at considerable expense, particularly when they are not in a position to play a significant role in the new technique.

D. FUTURE ALLOCATION PROCESS

Because the spectrum is a completely and instantly renewable resource, using it doesn't use it up. Since today's spectrum cannot be saved for tomorrow, restricting use for the sole sake of conservation has no intrinsic benefit. The purpose and only benefit of spectrum conservation is to create room for additional services now or in the future. As time passes additional services will require spectrum. To make room for these services, systems that now use a lot of spectrum should be replaced with improved technology when spectrum becomes crowded. Clearly, sufficient warning should be given before this replacement is required, so that investors can make proper decisions. In this regard, the spectrum managment procedure should review the alternative of installing more expensive systems using less spectrum now in comparison with the alternative of incurring a changeover cost in the future. The latter compares favorably with the former in proportion to the time span between the initial system installation and the time when the saved spectrum actually becomes needed. The review should recognize that what is being studied are two ways of conserving spectrum for a specified future need. There seems to be no intrinsic advantage to conserving spectrum before the time when it is needed. Because predicting the growth rate of technology is difficult, determining how much spectrum should be saved now for services in the immediate future is obviously a problem. When too little is saved now, there is inadequate room for a paced expansion of services and undesirably hasty spectrum saving measures should be taken by existing systems if worthwhile services are not to be denied spectrum space. When too much spectrum is saved now, the excess saved is wasted because it is not being used. If perfectly accurate predictions of the future could be made, spectrum policy extremes would always be avoided.

To allocate the radio spectrum mainly on the basis of a National Table of Frequency Allocations is inadequate to the complex interleaving of data technologies that is now possible. What is needed is a more flexible spectrum management technique in which the allocations of blocks of frequencies, time, and space are tailored to particular situations.

Much of today's equipment and many of today's operating practices result in severe spectrum wastage. Spectrum management techniques can tighten the efficiency of spectrum usage with all methods that prove economical. First, future spectrum management should be evolutionary. Changes in the system should be well thought out and amply prepared or the continued cooperation of those concerned will simply not be possible. Also, recovery of capital investment in equipment should be considered in planning for changes. But none of this means that evolution should continue at the snail's pace of the past.

Second, spectrum management thinking should continue to move away from the concept of controlling spectrum usage through simple but rather restrictive and rigid administrative rules. The movement should be in the direction of increasing individualized technical assessment of applications under explictly formulated priority criteria and under a more flexible employment of block allocation concepts. This will require much heavier use of analytical and data processing capabilities in the nation's spectrum management than at present. But it could result in stronger spectrum management capable of supporting the more flexible and effective management needed if fuller spectrum utilization is to be achieved.

Finally, spectrum management should require of the frequency manager a much more extensive understanding of telecommunications, basic technology and technological trends than has been required in the past when making frequency allocations/asignments. This knowledge is required not only to assess the priority of requirements but also to be able to predict impending requirements.

Thus, the spectrum manager should be fully cognizant of the available technology and of the plans and investments of the various services in order to make logical frequency allocations/assignments and ensure optimum use of the spectrum. If spectrum management is to be effective, frequency managers should immediately begin to prepare themselves to meet this challenge.

III. SPREAD SPECTRUM SYSTEMS

A. INTRODUCTION

With growing number of users crowding the radio spectrum and with conventional modulation bandwidths being squeezed to fewer Hertz per channel, any technological scheme that enables more room in the spectrum ought to be investigated. Recently. a technique known as spread spectrum has been growing rapidly in popularity and practicality. This system has been around since the 1950's, but it has been only recently that technology has made the system operational and cost effective.

Spread spectrum (SS) communications is an area where technology is outdistancing the radio regulations. The radio regulations admonish us to use the minimum bandwidth possible as a means of improving spectrum efficiency. However, no matter how logical this may seem, such a regulation may actually prevent us from implementing solutions to prevent spectrum crowding problems.

The numerous development programs sponsored by the military have produced a wide variety of SS techniques and designs. Three of the techniques to be discussed are direct sequence, frequency hopping, and SS hybrid. Although extensive advancements have been made in technology, there are still many unknowns regarding the application of the techniques to military operations and the establishment of frequency allocation/assignment policies and regulations. Within the military, study efforts on spread spectrum modulation techniques have already begun. However, analyses are required before the regulatory aspects of the techniques can be addressed. Therefore, the first step to introduce SS techniques is to define what actually is meant by the term "spread spectrum".

> Spread spectrum is a means of transmission in which the signal occupies a bandwidth in excess of the minimum necessary to send information; the band spread is accomplished by means of a code which is independent of the data and a synchronized reception with the code at the receiver is used for despreading and subsequent data recovery [Ref. 3: p. 855].

Under this definition the basic signal characteristics of modern spread spectrum systems are as follows:

1. The carrier is a nearly unpredictable, or pseudo-random wide band signal.
2. The bandwidth of the carrier is much wider than the bandwidth of the data modulation.
3. Reception is accomplished by cross correlation of the received wide-band signal with a synchronously generated replica of the wide-band carrier [Ref. 3: p. 856].

While spread spectrum methods and systems are important and with increasing technological improvements, they should not result in regulation since neither the ITU nor any other agency is ready to discuss the subject to the extent necessary for regulatory action. Moreover, at this point, the spreading schemes appear infinite in number while testing experience is minimal. Thus, considerable effort must be expended to evaluate such modulation techniques. Regardless, spread spectrum methods offer much promise and their development should not be unnecessarily retarded by premature regulation.

B. THEORY

In any communication system, the information rate is limited by three basic features of the communication channel: the inherent noise density, N_o (watts/Hz), within the channel, the channel bandwidth, W (Hz), and available signal power, P (watts). In principle, considering the basic properties, it is possible to encode information into either the power or bandwidth intensive domain. Each domain exhibits properties which the communication system designer can exploit to solve the problems of transferring information from the sender to the receiver with an arbitrarily small error rate.

The basis of spread spectrum technology is expressed by Shannon's law in the form of channel capacity, C (bits per second), given by equation 3.1,

$$C = 3.32 W \log (1 + P/N) \qquad \text{(eqn 3.1)}$$

where N is the channel noise power in watts. This equation shows the relationship between the ability of a channel to transfer error free information, compared to the power-to-noise ratio existing in the channel and the bandwidth used to transmit information [Ref. 4: p. 4]. It is not possible by any encoding method to send at a higher rate and have an arbitrarily low frequency of errors. This law is shown to hold true for the worst case of white thermal noise, for which each amplitude distribution is Gaussian.

In equation 3.1, the channel capacity is a function of three independent variables, W, P, and N. However, by proper normalization, this dependence can be essentially reduced to a single variable, noise power which can be expressed as:

$$N = N_o W. \qquad \text{(eqn 3.2)}$$

The available signal power and the channel noise density can also be used to define a new variable, W_o, such that

$$P = N_o W_o \text{ or } W_o = P/N_o , \qquad \text{(eqn 3.3)}$$

where W_o is the bandwidth which would yield a noise power equivalent to the signal power. Combining equations

3.2 and 3.3, the signal power-to-noise ratio can be expressed as:

$$P/N = N_o W_o /N_o W = W_o /W. \qquad \text{(eqn 3.4)}$$

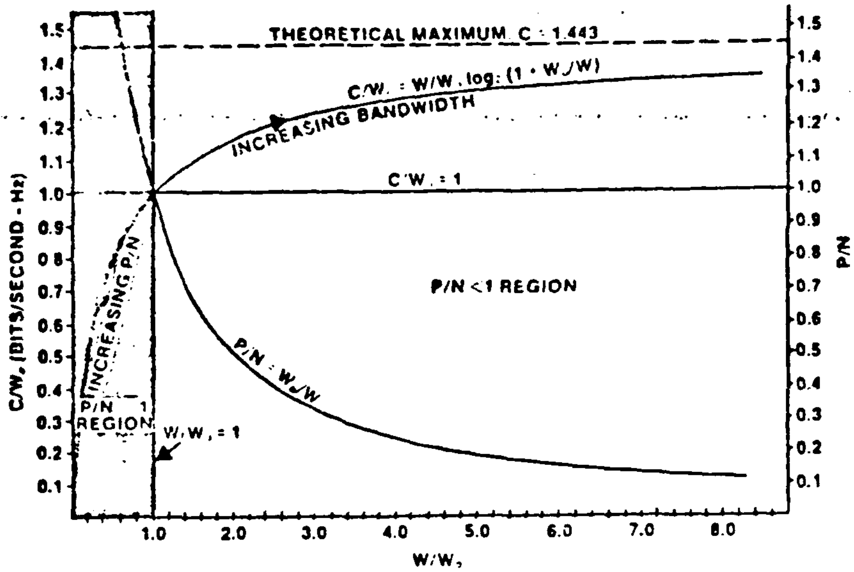
Thus, the power-to-noise ratio is equated to the bandwidth ratio. Substituting equation 3.4 into equation 3.1 and normalizing yields:

$$C/W_o = W/W_o \log_2 (1 + W_o /W), \qquad \text{(eqn 3.5)}$$

where W/W_o is the normalized bandwidth and C/W_o is the channel capacity. The normalized variable, C/W_o, reflects the systematic use of the available signal power and inherent channel noise density to effect communications within the channel.

The expression for channel capacity is now reduced to an expression where the normalized channel capacity is a function of a single independent variable, W/W_o. A plot of normalized channel capacity versus normalized bandwidth (equation 3.5) is shown in Figure 3.1. The channel power-to-noise ratio is also plotted on the same graph in order to aid in the interpretation of the expression.

Notice that normalized channel capacity decreases rapidly as the normalized bandwidth, W/W_o, is reduced below unity. In this region of the graph, shown shaded in Figure 3.1, the power-to-noise ratio is greater than one and increases rapidly as W/W_o decreases. This is the region traditionally used for reliable power domain communications.



[Ref. 5: p. 90]

Figure 3.1 Normalized Channel Capacity vs. Bandwidth.

However, another region exists, $W/W_o > 1$, within which information can also be transmitted within a channel. The power-to-noise ratio in this region is less than one and for that reason the information is not readily recoverable by a simple detection of signal power (as power domain communications would typically be detected). But if information is coded before it enters a channel and later decoded for detection, advantage can be taken of the P/N < 1 region of the spectrum for information transfer. These properties protect the signal from unwanted interference, from detection in the power domain, and provide near-maximum normalized channel information capacity.

Note that in Figure 3.1, to the left of the $W/W_o = 1$, $C/W = 1$ point, the curve of C/W_o is power-sensitive, whereas to the right of this point the curve is bandwidth-sensitive. The rationale for spread spectrum communications is to coherently convert the signal, before it enters the channel, from the power-intensive domain to take advantage of the $P/N < 1$ region. At the receiving end, the bandwidth-spread signal is converted as a standard power domain signal [Ref. 5: p. 89].

C. SPREAD SPECTRUM PRINCIPLES

Spread spectrum modulation systems are designed to permit communication of message information under the difficult conditions of very low signal-to-noise ratios (SNR) that may be encountered due to high co-channel interference (intentional interference) or low signal levels (transmissions with low detectability). The capability of spread spectrum systems to be operated at low SNR values is achieved by transmitting a signal that is distinct from all other signals, including interfering transmissions. Since over a time interval, T, a signal is characterized by 2WT numbers, the dimensionality of the signal (and hence the freedom to make it different from other signals) can be increased by increasing W, the bandwidth. Spread spectrum systems therefore use a bandwidth that is wide compared to the bandwidth that would normally be needed to communicate the message information.

The bandwidth (dimensionality) of the signal can be increased by amplitude or phase modulation. Although SS systems could utilize Gaussian noise as a modulating source, introducing both amplitude and phase variations, practical transmitter constraints on peak power and linearity favor systems which use phase modulation only. Additional limitations on the practical realization of equipment favor development of systems using discrete phase modulation (pseudonoise systems) and discrete frequency hopping (FH systems) rather than continuous modulation.

In principle the message information can be introduced by any of the conventional forms of amplitude, frequency or phase modulation. However, an additional requirement, usually placed on spread spectrum systems, is that the message modulation should only be recoverable by methods that require knowledge of the pseudonoise (PN) spreading code. This can be ensured by converting the message to a digital form and combining the digital message with the PN spreading code before modulation on a carrier. A spreading code is a signal that is mixed with a conventional radio frequency (RF) carrier for the purpose of spreading the bandwidth of the transmitted data. It should be stressed that spreading codes are usually linear in nature and are not used to encipher the signal.

D. SPREAD SPECTRUM SYSTEMS IMPLEMENTATION

Only recently has technology come to the point of making circuitry and systems reasonably small, reliable and inexpensive so as to enable practical implementations of spread spectrum concepts. Viewed as a motivating force encouraging the growth of the field, this recent development for practical spread spectrum systems must be reinforced by the additional pressure of more and greater demand being made on communication systems than ever before. Increased message traffic from a higher number of users is creating a need for protection of information from interference, not only in a military but in a commerical environment as well. As a result of these two major factors, the availability of systems and components coupled with the need for improved communication has thrust spread spectrum communications into the technical community.

There are many reasons for its inception, one of the principle factors being the desire for an antijam capability, usually in a single user application. As the advancements progressed, the SS concepts have been found to be well suited to precision range and position location and most recently have been applied to multiple access situations involving many users simultaneously.

Over the last fifteen years, the work in this field has been mainly associated with military applications. New programs in both military and commerical areas, using spread spectrum methods, are being conceived at an ever increasing rate. JTIDS, PLRS, SEEK TALK, HAVE QUICK, SINCGARS, and USC-28, to name a few, are such programs that are beginning to provide further momentum towards smaller, lighter, and more capable systems that are readily adaptable to volume production.

Therefore, the techniques which these programs may use are crucial. The tradeoffs between techniques used will determine what advantages or disadvantages will be enhanced or suppressed. Three of the techniques to be discussed in order to provide the reader with a more comprehensive view of spread spectrum capabilities are direct sequence, frequency hopping, and hybrid systems.

E. DIRECT SEQUENCE SYSTEMS

Direct sequence systems are the most common and widely used spread spectrum systems. Direct sequence signals are noise-like signals where the spectrum appears to consist of noise. In order to analyze the performance of the DS systems, it is necessary to be more specific about the operation of the modulation and demodulation equipment.

Thus, a definition of direct sequence that adequately reflects the operational characteristics of this technique is:

> Pseudorandom sequences, in which a carrier is modulated by a digital code sequence having a bit rate much higher than the information signal bandwidth [Ref. 6: p. 22].

These signals are usually modulated by phase shift keying the carrier. The wide bandwidth of these signals is due to the high rate at which the carrier phase is shifted. In a direct sequence system the bandwidth of the transmitted signal is directly related to the rate of the code (code bit rate). The mainlobe bandwidth is twice the code bit rate. Typical bandwidths for direct sequence signals is generally greater than one hundred times the traffic bandwidth, and therefore, the signals use a much wider bandwidth than is necessary for traffic transmission [Ref. 6: p. 25].

The carrier is directly modulated (phase shift keyed) by a spreading code which is a nearly random (pseudorandom) sequence of code elements. The primary purpose of modulating the carrier with a spreading code is to widen the bandwidth of the signal. The spreading code elements are generated at a higher rate than the traffic code elements. This causes the phase of the carrier to shift more frequently and therefore the bandwidth is increased.

Since the transmitted power of these signals is spread out over a wide bandwidth, the signal-to-noise ratio of a receiver must be considerably lower than that which is needed for reliable narrowband signal transmission. This low signal-to-noise ratio often makes it more difficult to intercept this type of signal.

F. FREQUENCY HOPPING SYSTEMS

A frequency-hopped communication method is a spread spectrum system in which the spreading of the spectrum is achieved by changing (hopping) the frequency of the carrier signal at regular intervals. The frequencies to which the signal can be hopped usually spaced equally across the desired frequency band and the signal is hopped to those frequencies in a seemingly random sequence called a hopping pattern. Typically, data transmission is accomplished by means of conventional binary or multitone frequency shift keying (FSK) modulation of the carrier signal. One or more bits can be transmitted using FSK during the time that the carrier signal is hopped to the nominal frequency. In effect, the modulated signal occupies a small band or slot centered around the nominal frequency. The frequency of the signal is hopped from slot to slot under control of the hopping pattern but the exact frequency within the slot is determined by the data modulated. It is also possible to use a hopping rate in excess of the data rate so that several frequency hops occur during the transmission of a single bit. This has obvious advantages if a jammer signal or other radio frequency interference is present in or near some of the frequency slots and also reduces detectability of unwanted signals. [Ref. 5: p. 82].

The frequency hopping technique is similar to that of direct sequence. The main difference is in the way the transmitted spectrum is generated and in the way interference is rejected. As with DS, a central feature is pseudorandom code generators at both the transmitter and receiver capable of producing identical codes with proper synchronization. As before, there is no restriction on the choice of information modulated. In the frequency hopping method, the pseudorandom code sequence is used to switch the carrier frequency instead of directly modulating the carrier.

The bandwidth over which the energy is spread is essentially independent of the code clock rate and is determined by the highest and lowest frequencies of the frequency hopped carriers.

G. HYBRID SPREAD SPECTRUM SYSTEMS

Another SS system that has increased in popularity in recent years is called a hybrid SS system. Hybrid systems are a combination of the above two basic techniques - direct sequence and frequency hopping. The use of FH, combined with DS techniques, provides significant improvement in performance and electronic counter-countermeasures (ECCM) reliability. The most attractive advantage of the hybrid SS system over a typical SS system is its survivability. This survivability is achieved due to its increased resistance to detection and interception (ECCM). This advantagc alone, plus the declining cost of technology, has created a market for this technique. Since hybrid SS systems can optimize the best functions of each technique, this mix of FH and DS can be developed to meet any projected threat and improve on technical performance [Ref. 14: p. 34].

H. APPLICATION AND ADVANTAGES

There are many reasons and applicabilities for spreading the spectrum and, if done properly, a multiplicity of benefits can accrue simultaneously. Three of the most important benefits are interference suppression, energy density reduction, and ranging or time delay measurement.

The most important of these is the suppression of interference which may be characterized as any combination of the following: 1) other users-intentional or unintentional 2) multiple access-spectrum sharing by coordinated users, and 3) multipath self-jamming by delayed signal.

Protection against in-band interference is called anti-jamming (AJ). This is probably the most extensive application of spread spectrum communications used today. A similar application is that of multiple access by numerous users who share the same spectrum in a coordinated manner, in that each employs signaling characteristics which are distinguishable from those of all other users [Ref. 7: p. 11].

The last form of interference suppressed by spread spectrum techniques is the self interference caused by multipath in which delayed signals, arriving via alternate paths, interfere with the direct transmission.

The second class of applications centers about the reduction of the energy density of the transmitted signal. It has a two-fold purpose, to meet international allocation regulations and to minimize detectability or provide privacy. The important point in this discussion is that the same level of average radiated power is required whether this power is spread over a very wide bandwidth or is concentrated in a very narrow bandwidth. Thus, the power spectral density radiated from a spread spectrum system is significantly less than the power spectral density radiated from a conventional narrowband system, as illustrated by Figure 3.2.

Another important consideration concerns the effectiveness and efficiency of spread spectrum systems. It can be shown that the number, N, of adjacent, narrowband channels (Figure 3.3) could be replaced by N/2 wideband channels as shown by Figure 3.4, but with multiple access capability such that spectrum utilization will be the same. What gives the

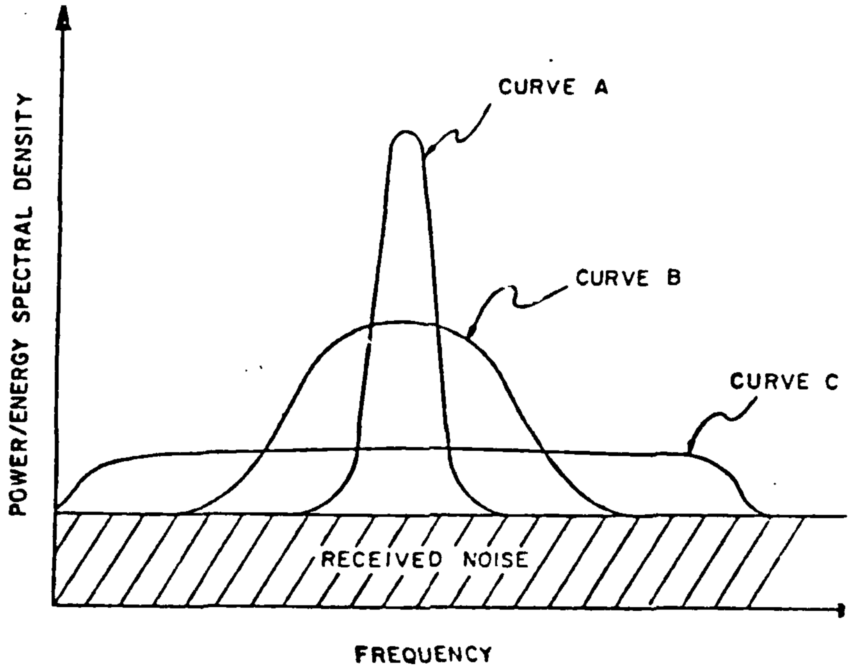


Figure 3.2 Comparison of Radiated Power Spectral Density.

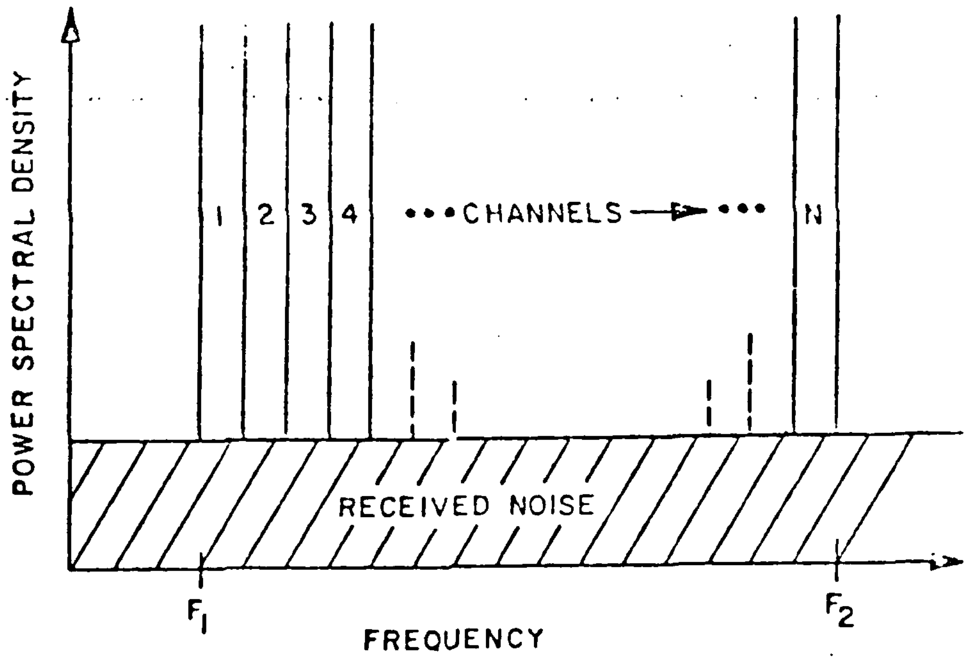


Figure 3.3 N Narrowband Channels.

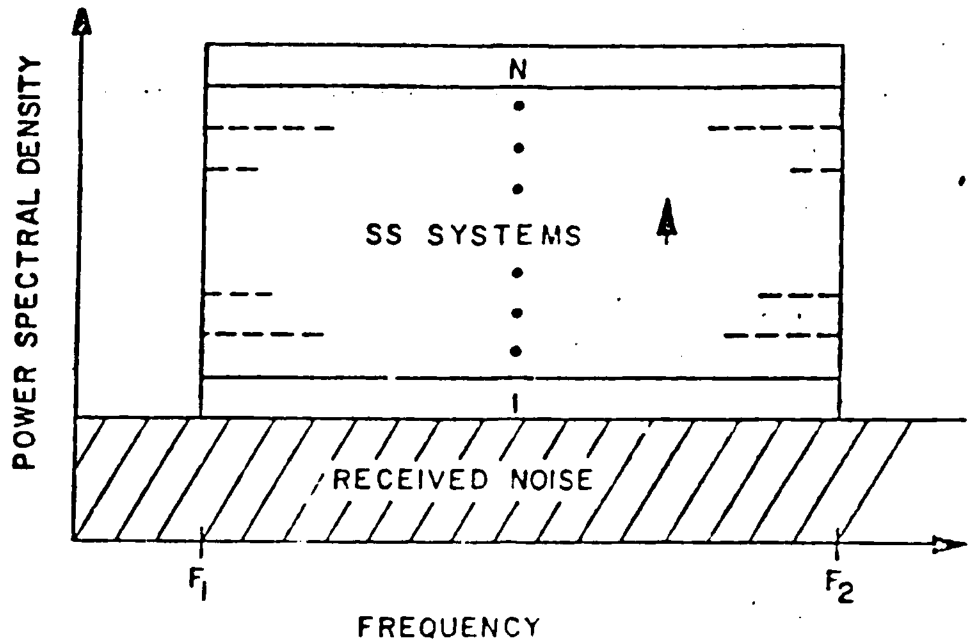


Figure 3.4 N/2 Wideband Channels.

spread spectrum systems their desirable advantage is that an spread spectrum receiver must be synchronized to the transmitter it is copying and thus, the spread spectrum receiver rejects undesired and unsynchronized signals. This, in turn, suggests the possibility that some number, n, of conventional communication systems can coexist with some number, m, of spread spectrum systems in a common frequency band and in the same electromagnetic spectrum environment shown by Figure 3.5.

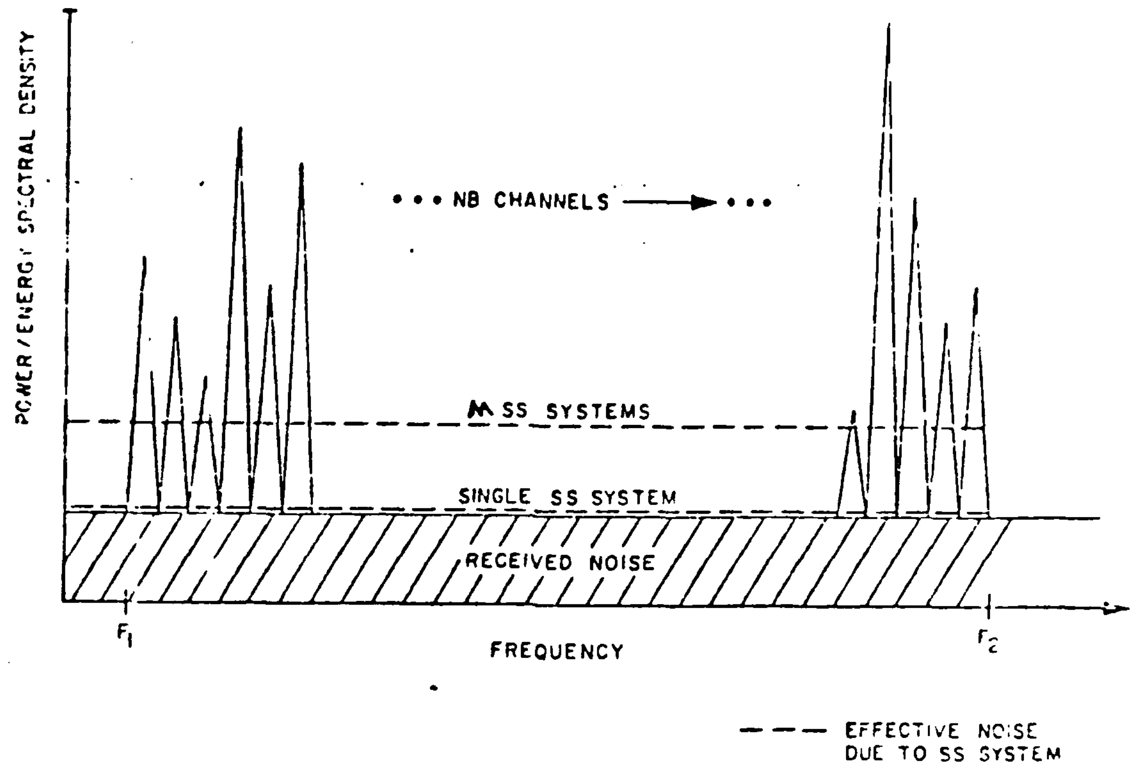


Figure 3.5   SS Systems Coexisting with Conventional Systems.

The application of spread spectrum for ranging or position location is rapidly gaining in importance. A common type of range measurement method used is radar. It consists of measuring the delay of a pulse or pulses from time of transmission to receipt. The advantage of spread spectrum ranging is that the timing measurement is made using the spreading code as the standard of measure. Highly accurate ranging measurements can be obtain when code bit rates are used. Thus, a spread spectrum system using 10 million bps code rate can provide ranging resolution to within 30 meters.

I. SPREAD SPECTRUM IMPACT ON SPECTRUM MANAGEMENT

The choice of spread spectrum technique may appear strange when the assumed goal of spectrum regulations is to conserve the frequency spectrum and certainly not use more bandwidth than necessary. Surprisingly, spread spectrum techniques solve a problem that at first glance they seem to create, that is, spectrum conservation (Figure 3.5). Traditionally, radio regulations tried to keep signals within the radio frequency environment separated by assigning each signal to an allocated frequency slot. However, there are other methods of separating signals, or in the general case, information sources. Consider the difference between Frequency Division Multiplex (FDM) and Time Division Multiplex (TDM). In the former, each information source is assigned a preselected frequency slot. In the latter, each information source, after being digitized, is assigned a time slot. In both multiplexing techniques, the parameter that maintains the separation is either frequency or time.

As a result of spread spectrum techniques developed over the years, a third signal multiplexing technique, called Code Division Multiplexing (CDM) can be identified. In this technique, both time and frequency are utilized. Each information source is assigned a unique orthogonal code which, when added to the original source data, spreads this data in frequency and pseudorandomizes the data in time.

Code Division Multiplexing allows communication system designers to actualize the potential of Shannon's law of trading signal power for bandwidth. Using this multiplexing method, many information channels can be established in the same frequency channel and at the same time, without interference between channels. Code Division Multiplexing may be the most promising spread spectrum technique because it allows implementation of a multiple access system in which many users can share the same channel in an unsynchronized way, with each user being assigned a different pseudorandom code.

However, the use of spread spectrum systems almost invariably introduces complications in frequency management. It is usually impossible to coordinate frequency band utilization among transmitters to provide a clear broadband channel for the communication function. As a result, a host of narrowband (NB) interferers have to be accepted as a consequence. Due to range disparity these NB interferers may be received many orders of magnitude stronger than the signal and thus some provision must be made for coping with these interferers.

There are numerous operational advantages for spread spectrum that, taken together, impact on spectrum management. Some of these advantages are [Ref. 8: p. 264]:

1. The use of a large number of frequencies in each waveform results in a form of frequency diversity that significantly reduces the degradation in performance that normally arises from rapid fading.
2. Any user can access the system at any time without waiting for a free channel.
3. There is no hard limit on the number of active users that can be handled simultaneously by the system. When the number of users exceeds the design value, the result is a degradation of performance for all users rather than denial of access.
4. Since all users occupy the same band, all user hardware is identical except for the filters associated with the unique signal set.
5. Under circumstances in which the full capacity of the system is not required, spread spectrum systems may coexist in the same frequency band as conventional narrowband systems without excessive mutual interference.

At this time the results are inconclusive and incomplete on how spread spectrum systems will impact on spectrum management. However, the numerous operational advantages, the more uniform and higher quality performance, and the ability to capitalize upon technological advances leads to the conclusion that such systems are serious contenders for the communication system of the future.

J. SPREAD SPECTRUM FUTURE TRENDS

Given the enormously growing complexity of the electronic environment, the exponential growth in technology has created new solutions and challenges for frequency managers. Most of the spread spectrum systems were developed and based on the 1970s technologies, which at the time did not allow implementation of any sophisticated SS techniques.

Today, a new era has dawned for the development and application of versatile, cost-effective SS systems which provide significant performance and flexibility enhancements. This new generation of SS systems is needed because fundamental new operational requirements have evolved and because technology such as complex digital functions can easily be implemented by using very large scale integration (VLSI) technology in small volume and at a reasonable cost.

Consistent with this trend, the hybrid SS System is becoming a leading candidate for employment. Given the significant evolution of the ECCM threat, it is expected that this trend towards hybrid SS systems will continue and future SS systems will probably seldom employ a single form of modulation. Instead a combination of modulation schemes will be employed to counter the threat. In the future, then, only hybrid SS systems may survive [Ref. 14: p. 86].

If hybrid systems are expected to survive, then why invest in other techniques? The best answer is probably the increased cost and the complexity of sophisticated techniques. A realistic viewpoint is unless other nations accept this type of technique to include standardization and interoperability requirements, the cost is almost prohibitive, and no acquisition of a hybrid SS system would be useful.

This problem is not new nor is it unknown to most who have been involved with international/national requirements. But because of its size and scope, the solution is to view it from a global perspective.

IV. A GLOBAL APPROACH FOR SPREAD SPECTRUM SYSTEMS

A. BACKGROUND

As the tendency continues to grow to develop SS systems, it becomes more apparent that these systems must be managed as a complete entity to create an integrated systems approach which will enable frequency managers/planners to meet worldwide requirements.

The quest for electromagnetic compatible (EMC) spread spectrum systems has led to newer, more sophisticated systems and techniques which provide significant performance and flexibility advantages over conventional systems. However, this new generation of EMC systems also proposes significant challenges and conflicts between wartime/peacetime and international/national requirements.

To meet these challenges the military working with industry must standardize their technical requirements to develop interoperability with other nations. This standardization would be the stepping stone which would ensure SS acceptance among all nations. Therefore, standardizing agreements for the use of SS systems to include host nation frequency approvals would establish a more effective, efficient, and prudent use of the spectrum in the best interests of all.

B. FREQUENCY ALLOCATION PROCESS

To achieve these interoperability standards and host nation frequency approvals, all new systems development must meet certain peacetime requirements including compliance with frequency allocation rules [Ref. 13: p. 3]. Currently, both the international and national radio regulations do not address SS systems; therefore, existing national and international notification, coordination, and registration procedures must be followed to obtain recognition/approval and protection at all levels.

To facilitate the authorization process and ensure that spectrum compatibility exists at any particular location, an EMC analysis is required. This analysis should consider cosite, intersite, and adjacent channel and band operations within the common electromagnetic environment. This necessity for compliance must be adhered to if the goal of spread spectrum acceptance among international and national users is to be achieved. Without their acceptance, the use of SS systems would be delayed until they are designed and developed in such a manner as to be consistent with the allocation tables and radio regulations.

In the final analysis, the approval to use SS systems will occur only after a significant test and coordination programs are developed and proved reliable. Currently, simulation and modeling technology has been incorporated into systems research, development, and test and evaluation programs to provide frequency planners with the tools necessary to make these decisions. These simulation and modeling techniques are helping to validate requirements by ensuring the most reliable and realistic way to employ SS systems. Thus, to determine the frequency bands that will be compatible with SS systems, an EMC analysis/simulation with present band users must be considered in detail by analyzing the possible interference effects of the systems (spread spectrum and conventional). Obviously, this must be resolved before each host nation will accept wide-scale use of spread spectrum systems.

C. FREQUENCY BAND SELECTION

During the SS systems development process a generalized frequency band could be identified for use, based on such restrictions as component availability, power, and propagation. Frequency allocation tables can be used to select candidate bands based on the service of the SS equipment. But, before a frequency band is selected, several interference problems must be analyzed in detail before acceptance is widespread. They should include near/far interference, impact of interference on spread spectrum systems, spread spectrum interference with conventional voice systems, and spread spectrum interference with conventional digital systems.

1. Near/Far Interference Problem

The near/far problem, which occurs when a receiver is located near an offending transmitter and is far from the desired transmitter, can be formidable when SS systems are employed. The problem can be experienced by SS receivers as well as by the conventional receivers that share the band with the SS systems. In operations involving only conventional radio systems, a receiver and any nearby offending transmitter would operate on different assigned channels. Usually they can be separated by several channels so that 40 to 80 dB of rejection results from receiver selectivity and transmitter RF filtering [Ref. 10: p. 9]. Because of this off-frequency rejection, the near/far problem can usually be avoided with conventional narrowband systems.

In operations involving SS radio systems, however, a receiver located near an offending transmitter that shares one or more channels with the receiver would not be able to obtain any off-frequency rejection. In this situation, a SS receiver must have sufficient processing gain to overcome the unwanted signal, while a conventional receiver must have a very narrow bandwidth to provide on-tune rejection of an unwanted SS signal.

To mitigate this problem, various techniques for rejecting unwanted signals must be employed. The attainment of EMC depends on how well unwanted signals can be rejected.

Thus, one of the major factors that will determine the practicality of applying SS techniques to military radio operations is how well unwanted signals can be rejected in receivers operated in environments that contain both conventional and spread spectrum systems. There are several means for rejecting signals. In each case, the amount of rejection obtained is usually dependent on the type of receiver and the nature of the unwanted signal. Thus, the rejection attainment in conventional receivers is often different from that of SS systems. A comparison of various means of rejection [Ref. 10: p. 13] is as follows:

1. Rejection resulting from Processing Gain-the correlator in a SS receiver yields an enhancement of the signal-to-interference ratio. The amount of enhancement, is referred to as the processing gain.
2. Off-Frequency Rejection -- conventional NB signals that are several channels or more from the channel used by the victim receiver can be attenuated 40 to 60 dB by the selectivity available in most conventional receivers.
3. On-Tune Rejection -- is determined by the chip rate of the SS signal and the intermediate frequency (IF) bandwidth of the victim NB receiver. For the present, SS systems are limited to bandwidths of about 200 MHz. Thus a conventional NB receiver

cannot reject SS signals nearly as effectively as it can reject adjacent-channel NB signals.

4. Signal Limiting Rejection -- unwanted signals of large amplitudes may be limited by the action of a limiter circuit or by amplifier saturation. If the unwanted signal occurs in short bursts and has a low duty cycle, such limiting can be an effective means of rejection because it reduces the average power of the interference. Therefore, the near/far problem does not occur in frequency hopping systems, since different code sequences imply different hopping patterns, so at most times the undesired signal will be on a different frequency from the desired one.

2. Impact of Interference on Spread Spectrum Systems

Frequency hopping interference from unwanted signals is produced when a frequency component of the de-hopped unwanted signal falls in the IF bandwidth of the receiver. This will occur in two situations. First, it will occur when the receiver code introduces a frequency shift in the receiver identical to the shift in the unwanted signal. Secondly, it will occur in a non-linear channel due to intermodulation between two or more interfering signals producing an intermodulation product at a suitable frequency with respect to the current value of the receiver [Ref. 11: p. 3-18].

For hopping rates that are high compared with the information rate, the interference produced from unwanted signals will be noise-like. This is because each spectral line will be spread in a $(\sin^2 x)/x^2$ fashion by an amount roughly equal to the hopping rate, and this spread will exceed the receiver information rate. For hopping rates low compared with the information rate, the spread on each line of the transmitted spectrum will be small compared with the information bandwidth, and the interference effects from unwanted signals will tend to be coherent. However, as the hopping rate is low (one or two hops per second) the occurrence of the interference will be intermittent with periods of one hop duration suffering heavy interference separated by long periods of interference free reception. The difference in the long term average performance from either high or low hopping rates is probably small, and a choice must then be made in practical systems as to what type of unwanted signal interference is preferable.

Direct sequence systems may be required to operate in the presence of other DS signals as might be encountered in multiple access situations in which many signals are assigned a common frequency band, where signals access a common repeater, or where there is transmission multipath in which delayed versions of the same signal are received. Assuming the pseudonoise (PN) code signal and the interference are uncorrelated, then it can be seen that by increasing the clock rate of the PN code the demodulator will be able to demodulate the message in higher levels of interference. Also, if there are several interfering signals, the interference power becomes the sum of the powers of the interfering signals [Ref. 11: p. 4-7].

The above statments are valid provided the desired signal and the interference are uncorrelated. If the code clock rates are the same, however, the signals cannot be considered to be uncorrelated. The spectrum then will depend upon the relative delay between the two clocks.

3. Spread Spectrum Interference with Conventional Voice Systems

For conventional communication systems, it was determined that approximately the same performance is obtained for a given amount of undesired power within the IF filter resulting from a DS signal or white Gaussian noise [Ref. 12: p. 284]. Additionally, the performance degradation to a conventional voice FM receiver caused by an interfering DS signal is greater than that encountered by conventional voice AM receiver.

Another interference effect on conventional systems is when the frequency separation between adjacent frequencies of the FH signal is reduced. When this occurs the FH signal increasingly contributes to performance degradation of the voice systems when frequencies other than the on-tune frequency are used. Thus, the same performance is obtained for the same in-band interference power even if the power is contributed by only the instantaneous spectra due to several frequency hops. Therefore, a frequency hopping interfering signal having only one of its frequencies hop within the IF filter would result in approximately the same performance as a periodic pulsed signal in which the dwell time of the hopper is equivalent to the pulse width of the periodic signal [Ref. 12: p. 284].

Additionally, performance degradation to a conventional voice AM (FM) receiver caused by a frequency hopping signal is slightly more (less) than that produced by a pulsed signal having a low hopping rate and a long dwell time, whereas, a frequency hopping signal produces slightly less (more) interference than a pulsed signal having a high hopping rate and a short dwell time. The leading candidate that is compatible with conventional voice systems is the hybrid SS systems. Tailoring both FH and DS advantages will help ensure acceptance worldwide.

4. Spread Spectrum Interference with Conventional Digital Systems

For conventional digital receivers, the interference power and waveform are related to receiver performance in terms of bit error probability. For other conventional receivers, performance degradation is measured in terms of an interference threshold for the specific waveform and receiver type. The main distinction is that verbal communication can take place without undue strain on either the talker or listener even if part of the transmission is garbled, but digital communication systems require error correcting codes to maintain the quality of the transmission.

Recent tests with typical FH systems have shown that the problem of burst errors which are caused by the inevitable presence of some jammed channels cannot be corrected with simple algorithms when their length exceeds tens of bits. However, the use of a hybrid system has a decisive advantage over the FH system because the effect of multipath propagation is reduced drastically by the correlation process of the DS modulation, and a high hop rate reduces the number of bits contained in each hop. Therefore, burst errors can be corrected with a simple algorithm embedded in the radio. This in effect, reduces the interference threshold to digital communications systems.

D. SPREAD SPECTRUM UTILIZATION

Although spread spectrum communication systems have been widely studied and used for specialized application, they are not usually considered to be efficient from the standpoint of spectrum utilization. However, when information theory is used to compare the number of simultaneous, compatible users of a finite segment of the spectrum which could be supported under two different operational schemes (narrowband and wideband) the results suggest that wideband or spread spectrum may enjoy a great advantage with respect to a NB system in terms of spectrum utilization theory.

One concern which arises continually is whether a multiple number of spread spectrum users transmitting in the same nominal carrier frequency and occupying the same RF bandwidth permits as many total users of that band as conventional frequency division channeling. A universal response to this question does not seem possible, because the relative number of users that can be obtained by either approach depends upon the model assumed for the user, signal power distribution, message length distribution, and charactistics of equipment used.

The approach to determining how many spread spectrum users can simultaneously occupy a given band is based upon the interference margin (M) of the system. This interference margin determines the signal-to-interference (S/I) ratio which can exist at the input to the receiver while maintaining adequate signal-to-interference at the output [Ref. 6: p. 30]. The equation for interference margin is

$$M = G-L-(S/I), \qquad \text{(eqn 4.1)}$$

where G is the SS processing gain and L is the system implementation loss. To illustrate equation 4.1, consider a SS bandwidth 1000 times that of the information bandwidth, so that G= 30dB and if S/I is required to be 10dB and L is taken as 2dB then the interference margin equals 18dB. Under these assumptions, the interference power could not exceed the wanted signal power by more than 18dB and still maintain the desired performance.

With some mathematical manipulation, it can be shown that the number of users possible in a given band is:

$$10 \log n = M+L = G-(S/I), \qquad \text{(eqn 4.2)}$$

where n is the total number of users.

Since in conventional allocation, a single channel is assigned to a single user, a much higher percentage of the available channels would be made available to users than by SS allocation. The exact number assigned is dependent upon how much spectrum is used to provide protection from equipment characteristics which cause interference over a band of frequencies wider than the required information bandwidth. Therefore, a low efficiency of spectrum use by SS systems occurs wher the users require continuous access to the communication channel or at least a high duty cycle. And, for such cases, bandwidth expansion systems are usually not spectrum use efficient. However, when each station or user is only transmitting a fraction of the total time, wideband systems provide greater communication capacity and spectrum utilization than do narrowband systems [Ref. 6: p. 30]. In a congested band operation, in which a service is assigned various bands of frequencies within the band, the communication capacity using broadband systems exceeds that of narrowband systems. Thus, as the number of users increases in a congested band operation, so that the S/N decreases, or as the duty cycle of operation decreases, broadband systems show increasing superiority over narrowband ones [Ref. 6: p. 31].

Thus, in an environment in which all users operate only on an assigned frequency, low duty cycle operation broadband systems give greater communication capacity for a given bandwidth allocated to the service. The reason for this is that for a low duty cycle, the narrowband system wastes spectrum because most of the allocated channels in the band will be idle at any given time. The narrowband allocation eliminates interference between users, while in the broadband case, each station appears as noise to the others. The broadband system takes advantage of the low duty cycle which keeps the noise level low and increases the per-circuit capacity.

At high duty cycles, the NB system results in superior spectrum utilization and it obviously makes sense to allocate spectrum using the conventional frequency division method for high duty systems. For low duty rate operations, in which large numbers of users rely upon a common relay point or which permit many users to operate on any of a number of frequencies in a band, bandwidth expanding systems can easily prove to be more efficient users of the spectrum.

In the final analysis, direct sequence spread spectrum efficiency is about double that for frequency hopping. This is tantamount to doubling the processing gain. However, FH technology may have an edge in achievable band spreading of one or more orders of magnitude over DS spreading technology which greatly overshadows the system's edge of direct sequence [Ref. 7: p. 18]. But incorporating into hybrid SS systems both the processing gain from DS and achievable band spreading from FH enhances the performance efficiency over each one separately.

E. RECOMMENDATION

In practice, the frequency band selection for spread spectrum systems should be made in a manner that complies with frequency allocation regulations to the maximum extent possible [Ref. 13: p. 18]. However, during the development stage military planners may want to consider not only the designated band for (primary) use but also multiple bands for (secondary) use during times of conflict.

V. POSSIBLE APPLICATION OF SPREAD SPECTRUM PRINCIPLES IN SPECTRUM ALLOCATION

A. BACKGROUND

Spread spectrum techniques have been developed in the past to permit communication of message information under difficult conditions of very low signal-to-noise ratio (such as may be encountered due to high co-channel interference), low signal levels, or transmissions having low detectability. They were not developed with a primary objective of spectrum use improvement, and yet the objectives for which they were developed appear to be desirable for spectrum allocation considerations. Three strategies for employing spread spectrum techniques that warrant further consideration as to their usefulness for increasing spectrum efficiency and system performance are frequency band sharing, dedicated spread spectrum band allocation, and entire spectrum band allocation.

B. FREQUENCY BAND SHARING

One strategy would be to overlay wideband spread spectrum users in selected frequency bands now assigned for a number of narrowband users and to use the frequencies simultaneously by both kinds of users. The burden of achieving and demonstrating practicality would fall on spread spectrum users because most of the spectrum in use today is already filled with narrowband users, and traditionally, new users of the spectrum carry a burden of establishing sharing criteria. An approach to implement this strategy would be to let present users continue operating as they are today and begin building an overlay of spread spectrum users on the present network. The spread spectrum users would be expected to develop their systems so as to create minimum interference to the conventional systems as well as being able to provide satisfactory operational performance of the spread spectrum systems in the presence of many interfering signals [Ref. 6: p. 29]. Spread spectrum systems should be evaluated the same as conventional systems. If a spread spectrum system complies with applicable rules, regulations, and procedures, the system should be afforded the same recognition and protection as conventional systems. However, if noncomplicance exists, the spread spectrum system should be allowed to operate on a noninterference basis, until such time as data can be made available to show compatibility. When rules are established, they should accommodate spread spectrum systems wherever possible. This strategy would be practical since, as summarized in preceding chapters, the spread spectrum signal is a low density signal (inherent because the signal power is spread over a wide bandwidth) which to the conventional system appears to be incoherent and is viewed as only small noise increase.

Additionally, the requirement that the spread spectrum system be able to operate in the existing interference environment is also implicit because of its inherent capability to provide interference rejection that is probably not matched in any other system. As discussed earlier, interference is rejected by the spread spectrum receiver up to some interference margin level which is a function of the code sequence rate in a direct sequence system and the number of frequency channels used in a frequency hopping system.

One recommended method for accommodating band sharing or band overlay is by assigning orthogonal codes. Only a receiver employing the same code sequence as the transmitter will be capable of decoding the transmitted signal and recovering the information signal. By assigning each receiver in a network different codes, the user may selectively address a particular receiver by employing the corresponding code at the transmitter. By assigning different code sequences to different systems, many transmissions can utilize the same portion of the frequency spectrum. This could be done without the explicit coordination necessary for trunking, time division multiple access, or frequency division multiple access. Transmitters will be able to communicate only with their intended receivers. In fact, each system should be unaware of the operation of other systems. This uncoordinated channel sharing is called code division multiple access (CDMA).

The main obstacle to the development of this strategy of overlapping spread spectrum wide bandwidth signals on existing narrowband systems is the reluctance of those currently authorized frequencies to share them when they appear to have nothing to gain. To overcome this obstacle, careful planning, cooperation, and experimentation must prove that the current users have nothing to lose and that society, as a whole, will benefit from increasing communication capability.

C. DEDICATED SPREAD SPECTRUM BAND ALLOCATION

The second strategy for accommodating spread spectrum systems in the frequency spectrum is to establish certain bands for spread spectrum systems and to assign orthogonal codes rather than frequency bands. One possibility for accommodating dedicated spread spectrum assignment and of alleviating some of the demand for the spectrum is to move to higher frequencies where there is less, or no, current usage. If systems can be designed to utilize frequencies above 10 GHz and handle the propagation effects at these higher frequencies, the bandwidth available for radio transmission will become several times the total of that used today.

One must consider that at frequencies above 10 GHz, atmospheric absorption by rain and fog as well as the high noise caused by higher temperatures make these high frequencies less desirable using current technology. The propagation effects for a spread spectrum signal is much the same as for any other signal, with the exception that wide bandwidths employed sometimes restrict system use [Ref. 4: p. 227]. The wideband modulation that can cause a system to be restricted in some areas can be an asset in other areas. Therefore, applying the correct spread spectrum technique and design at these frequencies may improve its performance over conventional systems.

This strategy could be implemented in an evolutionary manner as an outgrowth of the first strategy, if, because of their advantages, the number of spread spectrum systems overlaid in a band grew as narrowband systems diminished. Additionally, when advantages of spread spectrum techniques become more widely recognized, decisions could be made to implement spread spectrum systems in certain bands with code assignments, as suggested by Utlaut [Ref. 6: p. 30].

Finally, the management of frequency bands that encompass only spread spectrum systems could conceptually be simpler than the management of bands occupied by conventional narrowband and bandwidth expansion equipments. Once a band has been designated for spread spectrum use and the modulation technique determined, the primary concern is to ensure that the same spreading codes are not being used by more than one user. This could be accomplished through careful code assignment techniques and/or recordkeeping procedures.

D. ENTIRE SPECTRUM BAND ALLOCATION

The third strategy and possibly the least likely to be adopted is to develop a system that incorporates the entire frequency spectrum. Rather than limit the system to one frequency band which reduces its survivability to enemy detection and jammers, military systems could be developed that have the ability to expand to the entire frequency spectrum. This strategy would provide the capability for the military during peacetime to use its assigned frequency band but during times of conflict to expand to the entire frequency spectrum.

The main advantage to the development of this strategy is its superior performance in terms of flexibility and survivability. Flexibility provides the military a capability to select multiple bands for use based on the threat or host nation concerns. Survivability is achieved because the system is less vulnerable to sophisticated jamming from follower or transponder jammers. Whereas before the enemy jammers were built for certain/dedicated frequency bands, now they would need to cover the entire spectrum.

The main obstacle to this approach would be the reluctance of current users to allow the military this type of capability, where the potential is great that the military may use it during peacetime. To overcome this obstacle, military planners must insure that the only time the entire spectrum would be used is during wartime and that careful coordination would be achieved.

VI. CONCLUSION

Key to the continuing growth of radio systems is the availability of radio frequencies which can be used for communications. Without available spectrum, new services may be denied or forced to operate on frequencies already assigned. As a result of the inevitable increase in interference, existing services may be degraded and the new services will operate less than satisfactorily.

The philosophy of spectrum allocation has been one of sharing the inherent capacity of the radio spectrum among users by frequency division. As the number of users increased, methods were found to reduce the necessary bandwidth so that new users could be accommodated in the spectrum. As the user population continues to increase, it can be questioned as to whether frequency division allocation can continue to be the only way of allocating the spectrum, because this approach may not always be the most efficient way of using the spectrum.

Many of these difficulties arise from what is termed administrative convenience, which results from the sheer impossibility of making a proper EMC analysis of the impact of each new request for use of the spectrum on the existing users. As a result, assignment tables or rules based on antiquated data are used as a substitute. Revision of these rules in the light of new knowledge will be a lengthy and difficult process, but hopefully it will be accomplished.

Another successful approach is that of increasing the available spectrum into the higher frequency bands which currently receive little use. Because of the few users, rules and regulations are easier both to write and get accepted than are changes in existing rules. But the use of the higher frequencies is currently limited because of increased attenuation caused by rain and other forms of precipitation. More importantly, these higher frequencies are expensive to use because equipment costs are much greater than at the intensively-used lower frequencies.

Because of these problems associated with use of the higher frequencies, emphasis must be placed on more intensive use of the lower frequency bands for which equipment is readily available and which have propagation characteristics favorable to wide band communication over useful distances. The major problem is then one of increasing the efficiency of these already intensively used bands, thus allowing even greater use than is currently achievable. Such increased use implies that ultimately all channels will have to be shared between users. As a result, the performance of individual systems will be determined by the extent of interference from other users sharing the same channel.

Since the needs of the military for new telecommunication services is increasing faster than these services can be provided, technology can help stem the tide by better use of the available spectrum. The application of spread spectrum principles is one such way. Because of its technological characteristics, spread spectrum systems offers significant advantages to users, while at the same time it improves overall spectrum use. For the user, a SS system can be used to reject narrowband interference and to permit operations in areas where signal congestion would make communication using conventional systems impossible. At the same time, if the SS signal is used intermittently and if it is below the noise threshold of the narrowband receiver, it will not interfere with the narrowband user. Spread spectrum is clearly not the best answer to all problems in all circumstances, but in the critical and rapidly changing field of high density communications it may prove to be the best or possibly the only answer. This technological development can only be helpful if it is controlled by reasonable regulations which guide rather than hinder its usage. Spectrum managers must initiate these regulations which are necessary to insure orderly use of the spectrum, but this technological development should not be arbitrarily retarded by hasty regulatory action.

In the final analysis, three strategies for employing spread spectrum techniques, frequency band sharing, dedicated spread spectrum band allocation, and entire spectrum band allocation, all pose challenging problems to spectrum managers. No matter what strategy or frequency band is selected for spread spectrum systems it should be made in a manner that it complies with frequency allocation regulations to the maximum extent possible [Ref. 13: p. 18].

In summary, during the development stage military planners may want to consider not only the designated band for (primary) use but also multiple bands for (secondary) use during times of conflict.

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