

RECOMMENDATION ITU-R SM.1055

THE USE OF SPREAD SPECTRUM TECHNIQUES

(Question ITU-R 71/1)

(1994)

The ITU Radiocommunication Assembly,

considering

- a) that spread spectrum systems can offer improved sharing factors in certain conditions in achieving telecommunications objectives;
- b) that spread spectrum systems include frequency-hopping, direct sequence, and mixed frequency-hopping-direct sequence systems;
- c) that spread spectrum systems can offer operational advantages such as increased resistance to interference and improved performance under multipath conditions;
- d) that the mutual interference between spread spectrum signals, and between spread spectrum signals and more traditional narrow-band signals requires further study;
- e) that spread spectrum systems operate differently from more traditional narrow-band communications,

recommends

- 1. that the descriptions of spread spectrum technologies and signal-to-noise calculations contained in Annex 1, be recognized when describing direct sequence (DS), frequency-hopping (FH), and combination frequency-hopping/direct-sequence (FH/DS) modulations;
- 2. that the signal-to-interference ratios, the minimum required propagation losses, and other performance degradation measures between potential interferers as described in Annex 2 should be used when studying the effect of individual frequency-hopping and direct-sequence spread spectrum signals on several common signals on a one-to-one basis, including AM (A3E), FM (F3E), wideband FDM/FM (F8E), and television;
- 3. that the procedure described in Annex 3 be used when calculating the effect of direct-sequence and frequency-hopping systems on digital receivers, AM voice receivers, and FM voice receivers.

Note 1 – Additional studies should focus on the effects of multiple spread spectrum interferers in a crowded environment.

ANNEX 1

Spread spectrum techniques

1. Introduction

This Annex describes broadband “spread spectrum” techniques and the interference rejection capabilities of these systems.

A spread spectrum (SS) system can be defined as one in which the average energy of the transmitted signal is spread over a bandwidth which is much wider than the information bandwidth (the bandwidth of the transmitted signal is wider than the information bandwidth by at least a factor of two for double sideband AM and typically a factor of four or greater for narrow-band FM, and 100 to 1 for a linear SS system). These systems essentially trade the wider transmission bandwidth for a lower power spectral density and increased rejection to interfering signals operating in the same frequency band. They, therefore, have the potential of sharing the spectrum with conventional narrow-band systems

because of the potentially low power that is transmitted in the narrow-band receiver passband. In addition, high levels of interference will be rejected by SS receiving systems. These systems should therefore be examined to identify how efficiently they use the spectrum.

Two distinct types of bandwidth expansion SS techniques need to be discussed. These are the techniques that provide either linear or non-linear interference signal rejection. The classical FM approach typifies non-linear techniques because there is only an increase in the output S/N ratio (dB) when the input S/N is greater than the first or noise capture ratio. This means that the input S/N must be typically greater than 10 dB in order to obtain a linear enhancement against noise. In contrast to the FM type of system, the SS systems described in this Annex are linear so that the improvement remains constant even if the input wanted-to-unwanted signal ratio is negative. The output wanted signal-to-interference signal ratio $(S/I)_{out}$ is increased over the input wanted signal-to-interference ratio $(S/I)_{in}$ and is defined as the processing gain (PG) of the system. This PG might typically be 100 to 1, or larger. PG is defined by the following:

$$10 \log PG = (S/I)_{out} - (S/I)_{in} \quad (1)$$

A system with a PG of 100 (and no loss due to non-ideal signal processing) and a minimum output S/I of 10 dB requires that the input S/I is, at least;

$$(S/I)_{in} = 10 \text{ dB} - 10 \log 100 = -10 \text{ dB}$$

A linear SS system that can operate with an input (S/I) of -10 dB is extremely desirable since with an unwanted signal 10 dB higher than the wanted signal, the system can still be effectively used. For conventional systems with an input (S/I) of -10 dB, the wanted signal would be suppressed or "captured" and no information would be transferred.

A second major feature of commonly used SS techniques is that the resulting transmitted signal is a wideband low-power-density signal which resembles noise. Therefore, the transmitted signal is not readily detected by a conventional receiver. Recovery of the baseband information from the wideband transmitted signal can be accomplished only through correlation or matched filter (MF) signal processing. Because of this property, the unintended listener does not detect the baseband information, and because of the low power density, it may not cause any significant interference effects to other users of the spectrum. SS inherently provides a degree of message privacy to non-SS systems as well as other SS systems using different codes and no special signal processing. The coding also provides a selective addressing capability. Multiple users using different codes (code division multiple access – CDMA) can simultaneously transmit in the same frequency band with a minimum amount of cross interference (codes that are used should have a low cross-correlation function).

A third advantage of SS techniques over conventional modulation techniques is increased transmission reliability in the presence of selective fading and multipath effects. This advantage can be significant for typically encountered fading transmission mediums, e.g. in tropospheric scatter systems. Increased resistance to multipath is a direct consequence of spreading the transmitted bandwidth. As a first approximation, improvement is directly proportional to the ratio of transmitted bandwidth to information bandwidth. Receivers built to detect SS signals typically generate, prior to their final demodulation, a cross-correlation function between a replica of the transmitted signal and the signal received from the antenna. The correlation function of the wanted signal is always chosen to be as "good" as possible, i.e. maximum output at the centre and the signal falling to near zero in a time period equal to the reciprocal of the transmitted signal bandwidth and staying at near zero at all other times. Multipath degrades link performance when it combines with the direct signal in such a manner as to degrade the correlation function of the detected signal by reducing its peak value. The introduction of false trailing peaks into the correlation function due to simple multipath is typically not a problem. The receiver will detect and process the first peak of adequate amplitude, either the direct signal if it is strong enough or the first reflected signal of adequate amplitude if the direct signal is interfered with. In the latter case, timing becomes synchronized to the multipath return and it is processed in lieu of the direct signal. Consequently, for multipath to be destructive, it must occur with a differential delay less than the duration

of the peak of the correlation function, with a phase that causes destructive interference (cancellation rather than enhancement) and with an amplitude adequate to prevent the peak from exceeding detection thresholds. As the transmitted bandwidth is increased, the duration of the correlation function peak is proportionally decreased, and the multipath differential path delay that can affect performance is also proportionally decreased.

2. Spread spectrum signal types

Definitions for various types of spread spectrum techniques/signal structure are as follows:

- *Direct sequence (DS) spread spectrum*: a signal structuring technique utilizing a digital code spreading sequence having a chip rate $1/T_{s_{in}}$ much higher than the information signal bit rate $1/T_s$. Each information bit of the digital signal is transmitted as a pseudo-random sequence of chips, which produces a broad noise-like spectrum with a bandwidth (distance between first nulls) of $2B_{s_{in}} = 2/T_{s_{in}}$. The receiver correlates the RF input signal with a local copy of the spreading sequence to recover the narrow-band data information at a rate $1/T_s$.
- *Frequency-hopping (FH) spread spectrum*: a signal structuring technique employing automatic switching of the transmitted frequency. Selection of the frequency to be transmitted is typically made in a pseudo-random manner from a set of frequencies covering a band wider than the information bandwidth. The intended receiver frequency-hops in synchronization with the transmitter in order to retrieve the desired information.
- *Hybrid spread spectrum (FH/DS)*: a combination of frequency-hopping spread spectrum and direct-sequence spread spectrum.
- *Chip rate*: the rate at which the successive bits of the spreading sequence is applied to the signal information.

Two other types of spread spectrum modulation exist. The first uses pulsed frequency modulation or “chirped modulation” in which a carrier is swept over a band of frequencies. Radar systems, in particular, may use a sweep rate that is a linear function of time. The second spread spectrum type employs a non-sinusoidal carrier to provide additional processing gain. The following discussion does not include chirped or non-sinusoidal spread spectrum types.

3. Signal-to-noise (S/N) performance of DS and FH systems

The (S/N) performance of a linear DS spread spectrum system in the presence of Gaussian noise applies to receiver system noise and external noise with Gaussian characteristics. For this condition, DS performance is given by:

$$PG = \frac{(S/N)_{out}}{(S/N)_{in}} = 2 B_{s_{in}} T_s \quad (2)$$

where:

- PG : processing gain of the system
- $(S/N)_{out}$: output signal-to-noise ratio (correlator output)
- $(S/N)_{in}$: input signal-to-noise ratio (RF input)
- $2 B_{s_{in}}$: bandwidth of RF input signal power density spectrum at first nulls
- T_s : time duration of input signal information.

The processing gain (equation (2)) is considered the most important parameter of an SS system.

The peak of the code rate signal autocorrelation function at $u = 0$ will have a duration of the order $1/B_{s_{in}} = T_{s_{in}}$. The ratio of the duration of the signal information (T_s) to the main peak response is thus given by $T_s/T_{s_{in}}$. Thus the large $B_{s_{in}} T_s$ case affords a “pulse compression” effect whereby the signal energy in a relatively long pulse (duration of T_s) is “compressed” into a high level short pulse (duration of $T_{s_{in}}$). The result is a high detection probability at the intended receiver with no loss in time resolution.

The same results can be obtained in the time domain by taking the inverse Fourier transform of the respective functions and using equivalent time operations.

The FH system basically consists of a narrow-band filter matched to the information bandwidth pseudo-randomly shifting in frequency over the SS bandwidth. The noise out of the system is therefore governed by the bandwidth of the narrow filter. When an analysis is made of noise or an unwanted interfering signal which occupies the full hopping bandwidth, a decrease in the output unwanted signal power is obtained which is equal to the ratio of the bandwidths. The PG for this case is, therefore, equal to:

$$PG = \frac{B_{FH}}{B_s} \quad (3)$$

where:

B_{FH} : FH bandwidth

B_s : wanted information bandwidth.

If the FH system utilized the same RF bandwidth as the RF bandwidth in the DS system to the first nulls and transmits the same information rate, the B_{FH} and B_s in equation (3) are respectively equal to $2 B_{sin}$ and $1/T_s$ in equation (2) so that the processing gain of both systems is the same, neglecting second order effects. It should be noted that this is only for the case of a noise or an unwanted signal spread over the wide bandwidth and not for a narrow-band signal. The sensitivity of the FH system does not contain the PG improvement of the DS system and is simply proportional to the noise temperature of the system and the information bandwidth.

4. Signal-to-interference performance

The following describes the S/I performance of the DS and FH SS systems.

For the case in which the bandwidth of the input interfering signal (B_{lin}) is much less than the bandwidth of the input wanted signal (B_{sin}), the PG has been obtained as a function of the off-tuning ($\Delta\omega$) as:

$$\frac{(S/I)_{out}}{(S/I)_{in}} = \frac{2 T_s \frac{B_{sin}}{B_{lin}}}{\left[\frac{\sin(\Delta\omega / 2 B_{sin})}{\Delta\omega / 2 B_{sin}} \right]^2} \leq B_{sin} \quad (4)$$

where:

B_{lin} : input bandwidth of the RF interfering signal and all other terms are as defined in equation (2)

$\Delta\omega$: the radian frequency difference between the carrier of the wanted and unwanted signal.

The rejection of narrow-band interference by DS receivers may be understood as a process where the interference is greatly expanded in bandwidth (to approximately $2 B_{sin}$) by mixing with the spreading sequence in the receiver. The narrow-band filtering in the correlator removes all of the interference except for the portion left within the narrow bandwidth B_s of the desired signal.

Although narrow-band interference is rejected to a degree according to equation (4), the wide bandwidth of $2 B_{sin}$ could include a large number of narrow-band interfering signals. If one or more of these interferers is much stronger than the desired signal (possibly because of a near-by interfering transmitter and a far-away desired transmitter), it can overcome the processing gain for the DS signal and prevent proper operation of the system. This is known as the "near-far" problem. DS systems need to be designed such that they do not encounter interfering transmitters within the DS receiver bandwidth that are much stronger than the desired signal. Thus, the use of a wider B_{sin} to obtain higher interference rejection may cause a problem because of the larger number of interfering signals encountered within $2 B_{sin}$.

When the bandwidth of the interference is greater than the wanted signal, the PG has been obtained as:

$$\frac{(S/I)_{out}}{(S/I)_{in}} = \frac{2 \left(\frac{B_{lin}}{B_{sin}} \right) T_s B_{sin}}{\left[\frac{\sin \left(\Delta\omega / 2 B_{lin} \right)}{\Delta\omega / 2 B_{lin}} \right]^2} \quad (5)$$

This clearly shows that the gain is proportional to the bandwidth filtering ratio and the time bandwidth product as would have been expected. From the point of view of the output power ratios, the wideband SS system overcomes interference to the same degree that it overcomes noise.

In the FH SS system, the frequency hopper re-inserts the correct carrier frequency for the wanted signal and mixes it to the IF centre frequency. Any interfering signal, entering at a fixed frequency relative to the centre frequency of the FH SS system, is converted after the FH to a signal of reduced amplitude and random off-tuned frequency due to the FH mixer and IF filter action.

The interfering signal is then filtered so that effectively only those signals that fall within the same frequency channel as the desired signal are transferred through the system as interference. Since there are n possible frequency channels, this happens on an average only $1/n$ th of the time.

The interference at the input to the detector is, therefore, similar to a Poisson process. The degradation in the receiver output depends upon the signal processing structure. Since this structure heavily affects the degradation analysis, no simple generalization can be given for required input (S/I) ratios. However, the determination of what degradation results depends upon the structure of the receiver and the input (S/I) ratio.

FH systems do not necessarily suffer from the "near-far" problems that affect DS systems. Since a strong narrow-band interferer will affect only a small number of hops, it will cause only a small number of errors (which can be handled through forward error-correction techniques). A smart FH system may even note which hops contain interfering signals and choose alternative frequencies.

If the interference consists of a uniform wideband amplitude modulated (AM) signal that equals the FH bandwidth, the hopper output signal consists approximately of a constant amplitude signal with a random frequency offset term. For this case, the degradation analysis consists of essentially analysing an unwanted FM signal, reduced in power by the ratio of the bandwidths (equation (3)), against whatever subsequent type of signal processing structure is being employed by the frequency hopper. If the detection structure consists of a frequency modulated (FM) or phase modulated (PM) structure, the PG will be similar to that obtained against noise except for low (S/I) ratios where an FM capture effect will be introduced.

If the interference consists of a wideband FM signal that equals in bandwidth the FH bandwidth, the hopper output signal consists of a somewhat random amplitude signal with a random frequency offset. The effect of this signal would be very similar to the noise interference case so that the PG is given by equation (3) and the required (S/I) ratio is the same as required for the Gaussian noise case.

5. Spectrum efficiency

Since SS systems use more bandwidth to transmit a given amount of information than a conventional narrow-band system, the question of how efficiently the spectrum is being used should be considered. Spectrum use efficiency is generally a product of bandwidth, geometric space and time. The problem which therefore requires examination from the viewpoint of spectrum efficiency is how many narrow-band and SS systems can transmit simultaneously in the same frequency band and same geographical area, particularly for a high density of systems. This problem is under study in many arenas, with system designers trying to efficiently exploit the special characteristics of SS systems.

The use of SS systems in bands reserved for SS systems may prove to be a good solution for high-density mobile communications. In this case, the wide bandwidth of SS systems prevents the deep Rayleigh fading which occurs with conventional narrow-band systems, allowing lower power transmitters to provide reliable operation. Field tests of FH mobile radio equipment in the frequency band of about 800 MHz with Reed-Solomon coding and soft decision decoding have been carried out in Japan. The result shows a considerable reduction in bit errors, making use of the frequency-diversity effect. A laboratory experiment performed using a fading simulator showed a 17 dB decrease in required power for a BER of 10^{-3} . Similar results were obtained in a field test in urban areas, and in addition, the irreducible errors which are often encountered on digital transmission in mobile radio communications did not occur. Thus, it has been experimentally verified that the FH technique can tolerate significant fading in urban areas.

The spectrum efficiency issue should be addressed in detail in future studies on SS systems.

6. Summary

SS systems have been defined and descriptions of the DS, FH, and FH/DS techniques have been given. The PG has been shown for various interference cases to be proportional to the spread bandwidth divided by the information bandwidth. For many SS systems the PG can be a large positive number which allows the operation of the systems when the input interference is much greater than the wanted signal. This is the case in which the wanted output information would be lost for a typical narrow-band system. The large signal bandwidths required for many SS applications result in low power spectral density signals. Small numbers of these low power spectral density signals potentially cause negligible performance degradation to systems using conventional modulation techniques in the same frequency band, assuming that the total power density received from SS systems remains sufficiently below the desired conventional signal levels. In addition, SS systems can provide improved resistance to deep fading, resulting in system design advantages and improved spectrum efficiency.

ANNEX 2

Examples of band sharing by employing spread spectrum techniques

1. Introduction

A characteristic of a spread spectrum (SS) system is that the emitted signal bandwidth is typically much greater than the bandwidth of the message being transmitted. The large bandwidths and associated low power spectral densities used by these systems potentially make them less likely to interfere with conventional systems operating in the same environment, unless the number of active SS systems is large enough to raise the apparent background noise level.

Two sets of examples are given to show the potential sharing between SS and other modulation techniques.

2. Factors to consider in band sharing

The ability of two or more systems to share a band with an acceptable level of electromagnetic compatibility involves a number of factors specific to the systems being considered. In general, however, successful systems band sharing may necessitate a trade off between three conditions at the receivers of the systems.

Condition 1 – The wanted signal power delivered to the receivers must, with reasonable probability, exceed an acceptable threshold value to assure high detection probability of the shortest time duration signal element the receiver is capable of recognizing.

The factors influencing satisfaction of this condition are the conventional considerations that apply in any link calculation. Transmitter power should be the minimum needed as determined both by receiver sensitivity and expected variation in propagation path loss. Antenna characteristics should be consistent with coverage requirements. Receiver characteristics are the result of compromise at the designing stage to achieve sensitivity and dynamic-range balance and to account for transmitted signal tolerances and relative station motions.

Condition 2 – In the presence of interference, the signal-to-interference S/I ratio must exceed an acceptable threshold with reasonable probability. Typical factors influencing satisfaction of this condition are:

- interference power minimization by such techniques as transmitter power limitation, antenna nulling, low-duty-factor, and low spectral density;
- orthogonal signal structure designs that produce different exploitable characteristics where the S/I ratio can be enhanced by signal processing;
- receiver discrimination factors which take account of what existing receivers do rather than what is ideally possible.

Condition 3 – If Conditions 1 and 2 cannot be satisfied simultaneously, the application of other techniques may permit sharing. The signal design may include sufficient redundancy to permit recovery of received data when there is a detection probability failure for some fraction of unit signal elements (i.e., Condition 1 and/or Condition 2 are not always satisfied). This condition implies that it may be advantageous to re-design conventional systems to more robustly resist the effects of interference from SS systems, if SS systems are widely used. Typical factors influencing satisfaction of this condition are:

- redundant or diversified signalling structure;
- redundant information stream with error detection or correction capability;
- designs that employ memory either to retain the most current information or to extrapolate the most current information until the next update.

3. Example 1 – Interference from SS systems to conventional voice systems

3.1 General

Example 1 investigates the interference from SS systems to conventional voice systems. Two general types of SS signalling techniques of interest in this example are the direct-sequence (DS) and frequency-hopping (FH) techniques. The hybrid form employing both of these methods (FH/DS) is also of interest.

For two specified levels of performance, this Annex provides signal-to-interference (S/I) power ratios required for the protection of AM voice, FM voice and FDM/FM voice signals of systems operating in the presence of either SS or like-modulation interfering signals (i.e., AM, FM, and FDM/FM voice). The protection ratios were obtained for the case of a single voice receiver operating in the presence of one SS or like-modulation system. For several typical SS signals and a like-modulation signal, these protection ratios are used to calculate values of minimum propagation loss required to maintain the specified performance levels of the voice receivers so that comparisons can be made between the SS situations and the like-modulation case. It is shown that lower propagation loss values are typically required for unwanted SS signals than for unwanted co-channel like-modulation signals, and therefore a greater potential for sharing exists.

3.2 Protection ratios

3.2.1 Systems, signals, and performance levels

Representative AM and FM voice systems were selected for analysis. A 600-channel FDM/FM system, for which measured performance degradation data had been obtained, was also used in the analysis. The significant characteristics of systems used in the subsequent analysis are given in Table 1.

TABLE 1

Characteristics of A3E, F3E and F8E systems analysed

Modulation type	Receiver IF 3 dB bandwidth BW_{IF} (kHz)	Receiver antenna gain (dBi)	Receiver noise figure (dB)	Modulation index	Peak deviation (kHz)	e.i.r.p. ⁽¹⁾ (dBm)
A3E	8	3	6	1.0 ⁽²⁾	—	50
F3E	16	3	6	1.67	± 5	50
F8E (FDM/FM)	22 000	30	9	1.23	± 3 280 ⁽³⁾	60

(1) e.i.r.p.: equivalent isotropically radiated power.
(2) This number corresponds to a root-mean-square (r.m.s.) modulation index of 0.3 as given in Recommendation ITU-R SM.331.
(3) This number represents the total peak deviation.

Protection ratios were obtained for two performance levels of these systems when operating in the presence of DS and FH SS signals. The protection ratios were obtained in terms of the mean wanted signal to mean interference power ratio within the intermediate frequency (IF) filter referenced to the receiver input. The ratios determined for the FH case are also applicable to hybrid, FH/DS, SS signals. The two performance levels were taken to be articulation index (AI) values of 0.7 and 0.9, where AI is a measure of voice intelligibility, and the 0.7 threshold value separates the region within which there is no degradation to intelligibility from the region within which there is a degradation to intelligibility, and the 0.9 value, which is a tractable level for analysis, is between marginally commercial and good commercial quality.

3.2.2 Direct-sequence signals

For conventional communications systems, it was assumed that approximately the same performance would be obtained for a given amount of unwanted power within the IF filter resulting from a DS signal or white Gaussian noise. Available measured data and computer simulation results indicate that this assumption is valid for a relatively high rate DS signal. While measured data supporting this assumption are not available for A3E or F3E systems, measured data permitting comparison of DS binary phase-shift keying (PSK) interference with Gaussian noise are available for a binary FSK system and for a simulated 600-channel FDM/FM system different from the one described in Table 1. For these measurements, 40 Mbit/s DS signal and white Gaussian noise were individually processed through a filter having a 40 MHz 1 dB bandwidth, and adjustments were made such that the filter output power was the same in each of the two cases. The signal at the output of the filter was then used as the interfering signal at the input to the receiver being tested.

Note that DS systems with lower spreading code rates (such as used in many low-power and incidentally radiating systems) can have significant spectral density irregularities, which would modify the analysis.

3.2.3 Frequency-hopping signals

For conventional communications systems, it was assumed that approximately the same performance would be obtained for a given amount of unwanted power within the IF filter resulting from an FH signal or a pulsed signal. The assumption is based on a limited number of subjective listening tests during which an FH signal in an AM receiver was reported as sounding like pulsed interference. An FH signal randomly occurs on channel, while a pulsed signal occurs regularly. However, at typical operating performance levels, a randomly occurring pulsed signal with a mean rate of occurrence equal to the pulse repetition frequency of a periodic pulsed signal of the same pulse width, will have very nearly the same effect on the intelligibility of a voice signal as will the periodic pulsed signal.

Treating the FH signal as a pulsed signal, a significant amount of performance degradation data for pulsed interference to AM, FM, and FDM/FM voice receivers was reviewed to obtain the *S/I* protection ratios. To obtain a given value of AI, different *S/I* ratios are required for different pulsed signal parameters. The *S/I* ratio selected as the protection ratio for each case was the greatest value required to insure an AI of at least 0.7 or 0.9 for all values of pulse