Processing Gain in Spread Spectrum Signals.

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ABSTRACT

This paper addresses the processing gain (PG) characteristics of Spread Spectrum Systems. PG provides some unique properties to the Spread Spectrum waveforms that can primarily improve performance in the area of interference tolerance. The paper describes the benefits of processing gain and the reasons that the PG properties have been attractive for both military and commercial applications. It describes the signal processing required to implement such systems for Direct Sequence (DS), Frequency hop, and Hybrid Spread Spectrum Systems. The paper gives examples of applications that use the PG properties in communications systems. An overview of the maturity and the state of the art of presently available Spread Spectrum technology is also highlighted.

I.   INTRODUCTION.

Processing Gain (PG) is a term used to describe one of the unique properties of Spread Spectrum Waveforms. PG helps to measure the performance advantage of spread spectrum against narrowband waveforms. Spread spectrum waveforms are modulated twice. Once by using traditional modulation techniques such as PSK, FSK, etc. and then, for a second time with the wideband modulation of choice, i.e. Frequency Hopping (FH), Direct Sequence (DS) or Hybrid (FHDS). The wideband modulation tends to spread the signal energy over a wide range of frequencies. The wideband modulation is what provides the basis for the PG in spread spectrum systems.

Spread Spectrum is being used because of a number of attractive properties. Spread spectrum techniques had originally appealed to military systems applications. These attractive properties are partially attributed to the PG. They are used to improve:

- Anti-jamming performance.
- Low probability of intercept, and
- Multiple Access communications.

Commercial applications have adapted spread spectrum technology and they can extract parallel benefits. These are:

- Interference immunity.
- Low transmit power density.
- Multiple simultaneous transmissions.

II.   PROCESSING GAIN FOR FH SYSTEMS.

A Frequency Hop (FH) system obtains its wideband modulation characteristics by switching its narrowband signal over a wide range of frequencies in time. Figure 1 illustrates an example of a transmission for a FH system. This is a 3- dimensional figure with the horizontal axis being Time the y-axis being frequency and the z-axis being amplitude. As it is shown during FH the narrowband signal is " hopping " from frequency-to-frequency over time.   The narrowband signal is typically modulated using FSK modulation technique variations.

For a Frequency Hop system the PG is defined as the ratio between the instantaneous BW of each hop (narrowband signal) and the overall BW of the transmission channel in dB. The FH system avoids narrowband interference by continuously hopping to a new instantaneous frequency. The FH receiver is impacted by the interferer only when the signal happens to hop at the same frequency with the interferer.

This is best illustrated in Figure 1.   The interference area of coverage is overlayed on the 3- dimensional diagram that shows the FH transmission example. As shown on Figure 1, there are only three hop frequencies that have been impacted by the presence of the interference. The rest of the frequencies are interference free and the communications take place uninterrupted.   It is obvious from the example that the more instantaneous

frequencies are used and the wider the overall frequency BW is, the greater interference immunity is realized. This is because the signal spends less overall time on frequencies affected by interference. One observation is that FH waveforms can potentially avoid all together the frequencies covered by interference and use the remainder. Conceptually is a valid possibility but regulatory bodies require mandatory usage of all frequencies in a random fashion. This is to maintain a reduced average power density over all the frequencies used in the band.

III. PROCESSING GAIN FOR DS SYSTEMS.

For a DS system, random binary data with a bit rate of r_b bits per sec (bps) is multiplied (Exclusive Or'd) by a pseudorandom binary waveform, which is at much higher rate and it provides the frequency spreading operation. This pseudorandom (PN) binary source outputs symbols called chips at a constant chip rate r_c chips per sec (cps). This is a random noise like signal and hence the name PN signal. The chip rate is always higher than the bit rate, and the ratio of the chip rate to the bit rate in dB is defined as the processing gain. The PG can be viewed as signal to jammer (interference) ratio at the receiver after the despreading operation (removal of PN).

The larger the overall BW used, the higher the PG assuming a constant data rate. A higher PG implies greater immunity against interference. DS signals can actually operate at negative signal to noise ratios given that they possess enough processing gain.

The typical primary modulation for a DS signal is of the PSK variation. If for example the narrowband PSK requires an Eb/No of 12 dB to achieve a certain bit error rate performance, then a DS modulated PSK signal with a PG of 20 dB requires an Eb/No of -8 dB (12dB-20dB). One trade-off that must be carefully worked out is that of total BW vs. PG. The greater the BW the more total interference can potentially be interfering with the DS waveform.

Figure 2 illustrates the concept of processing gain for DS waveforms as seen at the receiver end. The unspread signal is the narrowband PSK signal before applying the wideband modulation. The spread signal is with the addition of the wideband modulation utilizing the PN code. It is apparent that the spread signal is wider in frequency BW but with lower power spectral density per Hz. The spread signal is actually shown to be close to the noise floor. PG for a DS system can be visualized as the jamming margin that exists as the difference between the unspread and spread waveforms.
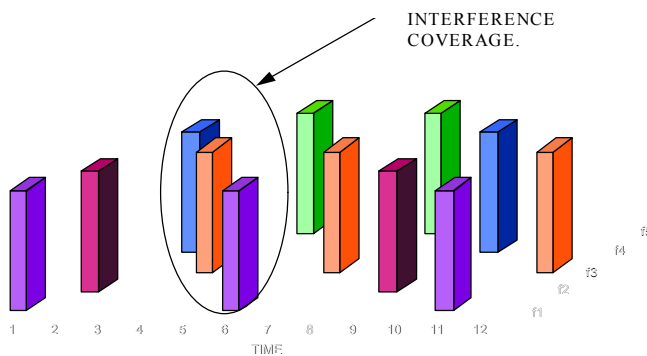

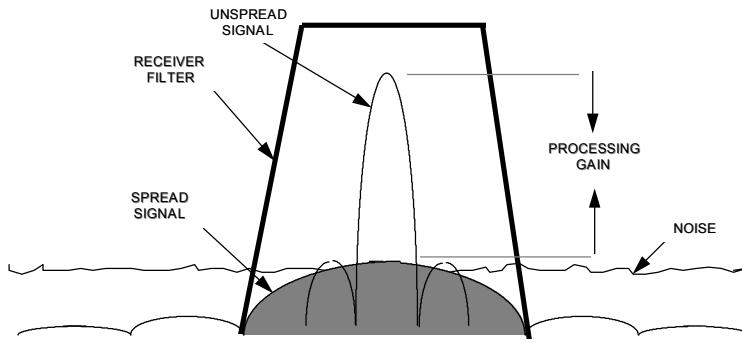Figure 1. FH Waveform in the Presence of Interference.

Figure 2. DS Processing Gain concept at the receiver.

The primary benefit of processing gain is its contribution towards interference resistance. The PN code spreads the transmitted signal in bandwidth and it makes it less susceptible to narrowband interference within the spread BW. The receiver of a DS system can be viewed as unspreading the intended signal and at the same time spreading the interfering waveform. This operation is best illustrated on Figure 3.

Figure 3 depicts the power spectral density functions of the signals at the receiver input, the despread signal, the bandpass filter power transfer function, and the band pass filter output. Figure 3 graphically describes the effect of the processing gain on a jammer. The interference (jammer) is narrow, and has a highly peaked psd, while the psd of the DS is wide and low. The despreading operation spreads the jammer power psd and lowers its peak, and the BPF output shows the effect on the signal to jammer ratio.

If for example, BPSK modulation is used and an Eb/No of lets say 14 dB is required to achieve a certain BER performance when this waveform is spread with a processing gain of 10 dB, then the receiver can still achieve its required performance with the signal having a 4dB power advantage over the interference. This is derived from the 14dB required minus the 10 dB of PG.

The higher the processing gain of the DSSS waveform the more the resistance to interference of the DS signal.

The classical definition of processing gain is the 10 $\text{Log}[r_c / r_b]$ in dB. By this definition a system that has a data rate of 10MBPS and a chip rate (rate of PN code) of 11MCPS will have a PG of 10.41 dB.
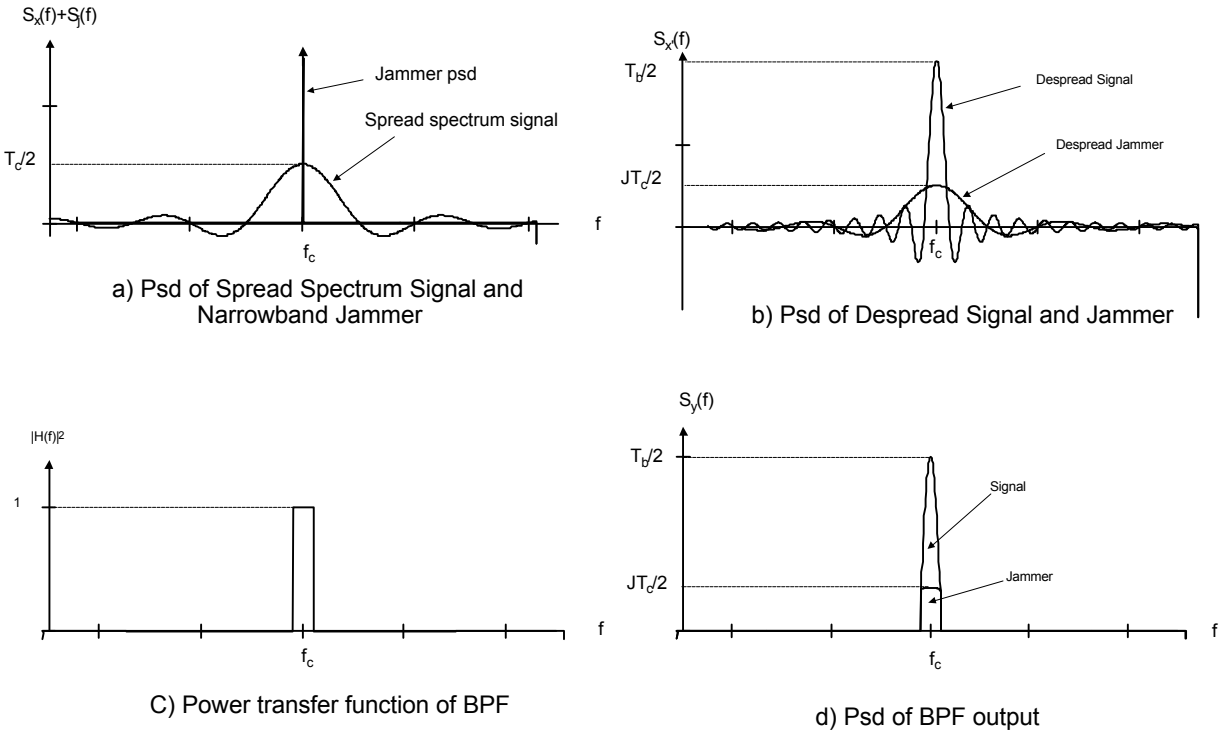
$S_x(f)+S_j(f)$

Jammer psd

$T_c/2$

Spread spectrum signal

f_c

f

a) Psd of Spread Spectrum Signal and Narrowband Jammer

$S_x(f)$

$T_b/2$

Despread Signal

Despread Jammer

$JT_c/2$

f_c

b) Psd of Despread Signal and Jammer

$|H(f)|^2$

1

f_c

f

C) Power transfer function of BPF

$S_y(f)$

$T_b/2$

Signal

$JT_c/2$

Jammer

f_c

f

d) Psd of BPF output

Fig. 3 Processing Gain Effect on Narrow Band Jamming

IV. PG USING THE PRISM[TM]

Harris Semiconductor has developed a state of the art DS radio chip set, the PRISM[TM] which implements the concept of PG. Using the PRISM[TM] chip set each data bit is x-ored with an 11 to 16 bit sequence. The processing gain is approximated as the 10Log[11-16] dB where 11-16 is the length of the PN code. If a code with a length of 16 bits is to be used then the processing gain is equivalent to 10 Log[16] dB or 12.04 dB. To this end these PN signals must possess certain mathematical properties to be useful as part of a DS system. Primarily the PN codes that are useful must have very good autocorrelation and crosscorrelation properties as well as maintaining some randomness properties.

The DS receiver is utilizing a reference PN sequence which is a replica to the transmitted sequence. When it detects correlation between the reference and the incoming sequences, it declares initial acquisition and establishes initial symbol timing. Any partial correlations can result in false acquisitions and degradation to the receiver performance. This is why the PN code must have good correlation properties.

Some of the PN code classes with such properties are described next.

Codes that have appropriate properties for DS receiver design include the Barker codes, Willard codes and m-sequences with 7 and 15 chips per period which are all implementable using the HSP3824, baseband processor of the PRISM[TM].

V. PG FOR HYBRID SYSTEMS.

Hybrid signals are a combination of FH and DS signals. The narrowband signal is spread in frequency as in DS and is also being hoped as in FH. For Hybrid systems, since they are a combination of FH and DS, the processing gain is the combination of the FH and DS PG's combined as one parameter. FHDS systems appear to be attractive in theory but implementation is quite challenging making them restrictive for practical applications.

VI. REFERENCES.

[1] J. Fakatselis, and M. Belkerdid, "Processing Gain for Direct Sequence Spread Spectrum Communication Systems and PRISM[TM]", Harris Semiconductor application note, No. AN9633, August 1996.

[2] Harris Semiconductor "1996 Wireless Communications Seminar Handbook", Melbourne FL., March 1996.