I. Introduction

Many users of radar today are specifying a Low Probability of Intercept (LPI) as an important tactical requirement. The term LPI is that property of a radar that because of its low power, wide bandwidth, frequency variability, or other design attributes, makes it difficult to be detected by means of passive intercept receiver devices such as electronic support (ES), radar warning receivers (RWRs), or electronics intelligence (ELINT) receivers. It follows that the LPI radar attempts to provide detection of targets at longer ranges than intercept receivers can accomplish detection of the radar. The success of a LPI radar is measured by how hard it is for the receiver to detect the radar emission parameters.

The LPI requirement is in response to the increase in capability of modern intercept receivers to detect and locate a radar emitter. In applications such as altimeters, tactical airborne targeting, surveillance and navigation, the interception of the radar transmission can quickly lead to electronic attack (or jamming). The LPI requirement is also in response to the pervasive threat of being destroyed by precision guided munitions and Anti-Radiation Missiles (ARMs). The denial of signal intercept protects these types of emitters from most known threats and is the objective of having a low probability of intercept. Since LPI radars typically use wideband CW signals that are difficult to intercept and/or identify, intercept receivers have a difficult time using only power spectral analysis and must resort to more sophisticated signal processing systems to extract the waveform parameters necessary to create the proper coherent jamming response.

This paper compares four intercept receiver signal processing techniques to detect the LPI radar waveform parameters. To test the four techniques, a variety of LPI CW waveforms were generated with signal-to-noise ratios of 0 and -6 dB. LPI waveforms generated include: FMCW, P1 through P4, Frank code, Costas hopping and combined PSK/FSK. Signal processing techniques compared include (a) filter bank processing with higher order statistics, (b) Wigner distribution, (c) quadrature mirror filter banks and (d) cyclostationary processing. The ability of each technique to extract the radar waveform parameters will be demonstrated. LPI waveforms being examined include frequency modulation continuous wave (FMCW), several polyphase coded CW waveforms (e.g., Frank, P4), frequency hopping and combined frequency hopping-phase coding. It will be verified that one technique alone is not sufficient to process the multiplicity of LPI waveforms available and that tomorrow’s intercept receiver design will have to use a permutation of several techniques.

II. Signal Processing Techniques Evaluated

The signal processing techniques used to extract the LPI radar parameters are described briefly below.

Filter Bank And Higher Order Statistics

The filter bank and higher order statistic technique (shown in Figure 1 is based on the use of a parallel array of filters and higher order statistics (cumulants). The objective of the filter bank is to separate the input signal in small frequency bands, providing a complete time-frequency description of the unknown signal. Then, each sub-band signal is treated individually and is followed by a third-order estimator that helps suppress the noise. The parameters extracted can then be used to create the proper jamming waveform to attack the radar [1].
The Wigner distribution (WD) has been noted as one of the more useful time-frequency analysis techniques for LPI waveform parameter extraction [2]. The Wigner distribution is defined as [3]

\[ W(t, \omega) = \int_{-\infty}^{\infty} f(t + \tau/2) f^*(t - \tau/2) e^{-j\omega \tau} \, d\tau \]

This continuous time and frequency representation can be modified for the discrete case as

\[ W(l, \omega) = 2 \sum_{n=-\infty}^{\infty} f(l + n) f^*(l - n) e^{-j2\pi \omega n} \]

Further modification results in the pseudo-Wigner distribution or windowed-Wigner distribution

\[ W(l, \omega) = 2 \sum_{n=-N+1}^{N-1} f(l + n) f^*(l - n) w(n) w(-n) e^{-j2\pi \omega n} \]

where \( w(n) \) represents a moving window function centered about \( n \). The Wigner distribution (with cross-terms included) can reliably extract the waveform parameters with only a moderate amount of processing needed to derive the kernel function.

Quadrature Mirror Filter Bank
A three-layer quadrature mirror filter bank (QMFB) tree is detailed in Figure 2 and performs a wavelet decomposition of the input signal to detect the LPI waveform parameters [4]. In this example, a 16 sample input waveform with a bandwidth of \( \pi \) is used. If the input signal is squared, this waveform can be thought of as a series of tiles in which each of the 16 tiles represent the energy in the entire frequency spectrum of the signal at that time.
This input waveform is then fed into the first QMF pair that consists of a high pass filter and a low pass filter. Since the filters have a $\pi/2$ bandwidth, only half of the samples out of each filter are required to meet the Nyquist criteria. Therefore, each output is decimated by two, giving the same number of outputs from the layer as there were inputs. The energy matrix out of the first layer is twice as detailed in frequency and half as detailed in time as the original. In other words, each tile represents the energy contained in the signal for two time samples over a frequency range of 0 to $\pi/2$ (low pass filter output) or $\pi/2$ to $\pi$ (high pass filter output). This is shown in the figure by noting that the tiles out of the first layer are twice as wide, but half as tall, as the original. The inputs of each layer are the outputs of the previous layer. This continues for however many layers are needed to obtain the required frequency detail of the LPI signal.

Cyclostationary Signal Processing

Digitally modulated signals are cyclostationary. This means the probabilistic parameters (mean value and correlation) vary in time with single or multiple periodicity. One property that extends from this is that they have spectral correlation or the signal is correlated with frequency-shifted versions of itself at certain frequency shifts.

The advantage in the analysis of LPI waveforms using cyclostationary modeling, is that non-zero correlation is exhibited between certain frequency components when their frequency separation is related to the periodicity of interest (e.g., the symbol rate or carrier frequency). The value of that frequency separation is referred to as the cycle frequency. The spectral correlation properties of a signal are evident in a plot of the Spectral Correlation Density (SCD) function. A block diagram of the FFT Accumulation method is shown in Figure 3 [5].

III. References


