Enabling Technology: Radar PRI and RF Prediction

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Abstract

In order to gain signal-processing advantages or gain resilience to ECM, many radars employ pulse-to-pulse PRI agility, a few employ pulse-to-pulse RF agility and some employ both forms of agility. This PRI or RF agility can be in the form of a ramp, a multi-element stagger, a dwell-shift or even a sinusoidal variation (wobbulated RF is common in radars which use a spin-tuned Magnetron transmitter for example). Pulse-to-pulse agility makes it difficult for a deception jammer to produce credible false targets. However, by introducing the capability to predict both the time of arrival and radio frequency of each pulse a significant increase in ECM effectiveness can be achieved.

PRI and RF prediction can complement existing ECM techniques making them more robust as well as adding new features to the jammer such as: coherent up-range false targets, Range Gate Pull In, range pulls beyond a PRI, Coherent Range Bin Masking, de-interleaving of multiple radar signals, and lower jammer power requirements. Predictors developed by MC Countermeasures Inc. now offer the capability to predict both the time of arrival of each pulse and its RF frequency thereby complementing virtually any ECM system.

This paper presents how PRI and RF prediction can be utilized to improve ECM effectiveness. As well, it discusses some of the fundamentals behind PRI and RF prediction along with various challenges. Furthermore, it shows a straight-forward approach to adding a predictor to either an existing or a new deceptive jamming system by describing various possible configurations.

Introduction

Many of today's electronic countermeasures (ECM) system support deceptive jamming using either a digital RF memory (DRFM) or a fast-tuning voltage controlled oscillator (VCO). These systems can produce false targets up-range and down-range achieving range gate pull in, range gate pull out (RGPI/RGPO) and cover-pulse techniques against radars with a constant pulse repetition interval (PRI). However, unless PRI prediction is used, only down-range techniques are possible against radar modes which employ pulse-to-pulse PRI agility. In addition, the signal environment and system limitations such as multiple emitters within the jammer's instantaneous bandwidth (typically several hundred MHz), dropped or missing pulses from individual emitter pulse trains, and a lack of simultaneous transmit and receive capability can impact ECM effectiveness in the field.

In order to increase effectiveness of ECM assets it is imperative to properly control them. A tool for gaining this control is PRI and RF prediction. Using the time of arrival (TOA) and radio frequency (RF) of the incoming pulses, a user can position coherent targets up-range, filter the emitter based on TOA and account for missing information. As well, when using these TOA predictions, a user can make optimal use of the jammer receiver / transmitter to produce a variety of ECM's.

This paper introduces the concepts and benefits of PRI and RF prediction and discusses several ways in which real-time pulse-to-pulse PRI and RF prediction can greatly enhance the performance of an ECM system. This is done by compensating for missing and spurious pulses and filtering multiple emitters so that each can be isolated and one or more selected for active jamming. Applications such as controlling a single ECM asset; enhancing ECM techniques; controlling a receive/transmit scheme for a typical pod mounted jammer application; and reducing power requirements are also covered.

Radar Background

Before proceeding to PRI prediction let's glance at the evolution and current state of radars and electronic countermeasures. Table 1 presents radar types, based on pulse repetition frequency (PRF) and their respective modes of operation and characteristics. This is followed by a short discussion of various electronic countermeasures and how PRI and RF prediction fits in.

Table 1: Radar Characteristics

Type	PRF	Characteristics
Pulsed Doppler Illuminator	Up to 500 KHz	• Constant PRI (Coherent) • Approximately 50% DC • Semi-active illumination for missile seeker
High PRF Pulsed Doppler	75 to 250 KHz	• Constant and Dwell-Shift PRI (Coherent) • Tracking in Doppler • Gating in range
Medium PRF Pulsed Doppler	15 to 75 KHz	• Tracking in Doppler and range, both ambiguous • Needs staggered PRI to extend unambiguous range • Staggered PRI also helps eliminate blind speeds in moving target indicator (MTI) filter
Low PRF Pulsed Doppler	5 to 15 KHz	• Often non-track mode (acquisition) • Coherent MTI for clutter rejection • Range measurement, Doppler and MTI filtering • Staggered PRI tailored to suit MTI filtering
Low PRF Radars	100 Hz – 5 KHz	• Older non-coherent acquisition and track radars • Long range search • Many are pulse-to-pulse Radar Frequency (RF) agile • Complex PRI stagger patterns

Electronic Countermeasures

For some older non-coherent radars, since they are susceptible to noise jamming, there is no urgent need for PRI Prediction capability. These radars have a wide instantaneous bandwidth making it relatively easy to get high levels of noise into the radar's front end to mask out target returns, independently of range. However, RF agility forces the noise jammers to spread their output power over several hundred MHz, so that extremely high jammer effective radiated power (ERP) is required. In these cases, PRI and RF prediction would be beneficial in reducing the jammer's ERP.

With the introduction of burst-to-burst RF agile radars and coherent radar processing with narrow bandwidth Doppler filters using bandwidths of only a few 100 Hz, noise jammers were rendered less effective. In response to these narrow band filters in the radar, jammers made use of fast tuning oscillators to attempt to mask the target return using noise in the proper RF band, however with tuning accuracy limited to a few MHz, the noise was still spread out over a relatively wide bandwidth. In fact, the noise signal in the radar's bandwidth is approximately 40 db down (20Log[1MHz/100Hz]) and the radar may still acquire the target.

As noise jamming did not seem to be an ideal option for jamming these types of radars, radar deception was introduced with the idea being to create false targets and mislead the radar rather than employ brute force noise techniques. Early (and indeed some current) deception jammers used analog delay lines to capture the radar pulse and output it shortly afterwards. With this technology it was possible to implement range gate pull off techniques (RGPO) so that the radar's range gate would follow the false target return away from the real target return. Analog delay lines can produce down-range false targets within a very limited range, 10 µs maximum; after which they experience significant signal loss and the technique is ineffective.

In order to produce up-range as well as down-range false targets over the full PRI, digital radar frequency memories (DRFM's) were developed to capture and store each radar pulse. However, only down-range false targets are possible when the PRI is agile pulse-to-pulse since the DRFM reads are usually triggered a fixed delay after the radar pulse. Since producing up-range false targets for non-constant PRI patterns is essential for better radar deception, this creates the need for PRI prediction in order to determine the time of arrival for the next pulse and vary the read delay on a pulse-to-pulse basis.

As for RF agile radars, both VCO's and DRFM's can be used in a set-on configuration where the RF of the pulse is measured and the jammer is then quickly tuned or set-on to the correct frequency. In this mode of operation ECM is limited to down-range techniques since the RF changes pulse to pulse. As a result, it is necessary to predict the upcoming RF to create up-range techniques to either tune a voltage controlled oscillator (VCO) or perform an RF shift of the DRFM contents.

Impact of PRI Agility on ECM Techniques

Many military radars have one or more modes of operation in which the PRI is varied on a pulse to pulse basis. This might take the form of a staggered PRI pattern in which a frame consisting of "n" PRI or positions is formed by a sequence of "m" distinct PRI values or elements. This is referred to here as an m-element, n-position stagger. A pattern with 5 distinct PRI elements (1, 2, 3, 4 and 5) staggered over 25 positions is shown below in Figure 1.

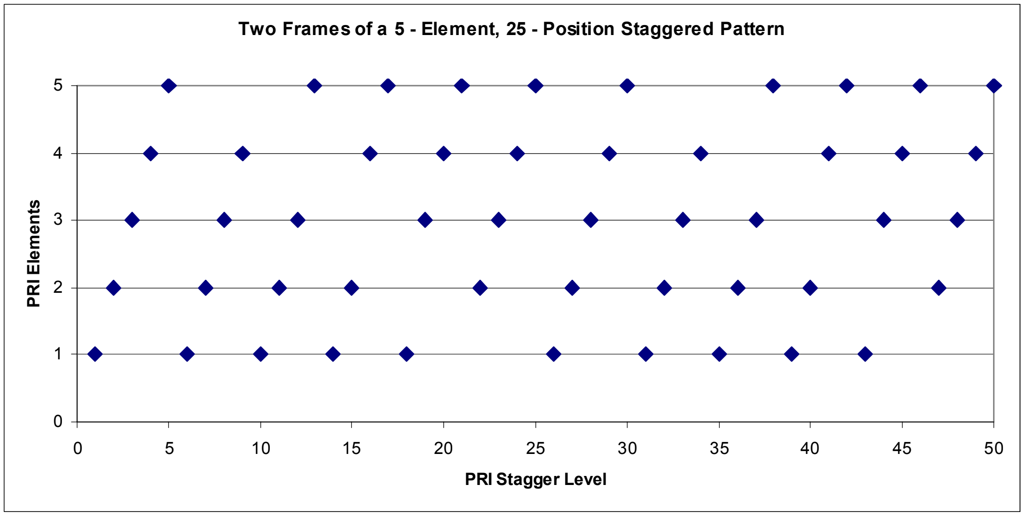

Figure 1: Illustration of a 5-element, 25-position staggered pattern.

PRI agility could also be implemented as a sliding pattern in which the PRI is incremented (or decremented) by a fixed amount on each interval or it might even take on the form of a sinusoidal variation as a function of time. Many “constant” PRI radar modes, such as high PRF pulsed Doppler, require minor adjustments of the PRI in order to eliminate eclipsing which occurs when the target return pulse coincides with the radar’s transmit pulse. This form of agility is referred to as dwell-shift. PRI Prediction is easily accomplished when the pulse interval is constant, however it is not so simple when the pulse interval is staggered, sliding or wobbulated (sinusoidal). Even dwell-shift can be a problem if the PRI change is not quickly detected.

Any form of PRI agility causes problems even for a DRFM-based jammer since it cannot adjust the timing of its false targets on a pulse to pulse basis in order to generate up-range false targets if it cannot predict when the next pulse will arrive. This would limit the jammer’s ECM techniques to down-range false targets, which can then be filtered out by ECCM techniques such as leading edge track and guard gates. Because of the inherent through-put delay of a repeater jammer, even coverpulse techniques are compromised. In many cases, the solution has been to increase the jammer’s transmit power, which can be very costly in terms of prime power, size, weight and cooling. Accurate PRI prediction provides a much simpler, more effective solution without the attendant costs associated with high transmitter power.

Impact of RF Agility on ECM Techniques

In a fashion similar to that of PRI agility, certain radars can change the radio frequency (RF) on a pulse to pulse basis. This quickly limits a DRFM-based jammer or voltage controlled oscillator (VCO) jammer to down-range only techniques since the pulses need to be captured (or RF measured) before being repeated. System throughput delay can also eliminate any possibility of returns close to the video skin. The RF agility can take the form of a stagger pattern of length “n” which is formed by a sequence of “m” RF values,. It might also be a sliding pattern in which the RF is incremented (or decremented) by a fixed amount on each interval. Or RF agility might take the form of a sinusoidal variation as a function of time when generated by a spin-tuned magnetron transmitter. Precise RF prediction permits smarter noise jamming, the generation of up-range false targets that integrate non-coherently, and greatly reduces the power required for effective ECM, possibly by 10-20 dB.

What is PRI Prediction?

PRI Prediction is more than just PRI tracking. Although tacking does form part of the whole prediction algorithm, prediction goes well beyond the idea of conventional PRI tracking. PRI Tracking traditionally requires (many) multiple frames of the pattern to be analyzed before the PRI pattern can be understood and then tracked, while PRI Prediction is pulse-to-pulse real-time adaptive. PRI Prediction can successfully predict what the time of arrival of the next pulse will be after only a few pulses rather than a few frames.

The ultimate goal for PRI prediction is to assist in the production of coherent up-range false targets so that break-lock, coverpulse and counter-acquisition techniques can be used effectively by allowing the ECM to start earlier. If the time of arrival of the next radar pulse can be predicted accurately, then false targets can be positioned at a fixed delay ahead of that time.

Illustrated in Figure 2 below is a false target positioned with a fixed delay after each received radar pulse where the PRI changes pulse-to-pulse. Note that the false target appears to be at a different up-range position on each PRI and hence would only be integrated by the radar as a return that is down-range from the jammer platform.

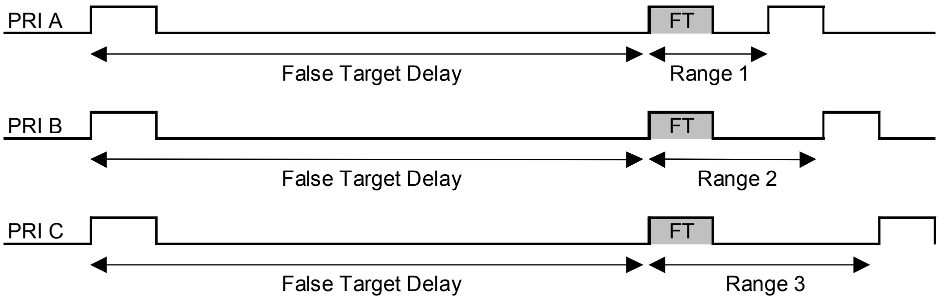

Figure 2: Without Prediction: Near Up-Range False-Target Becomes Far Down-Range False Target

In order to create viable up-range false targets, the techniques generator needs to know the exact time of arrival of each radar pulse so that it can vary the false target delay by the appropriate amount with respect to the previous pulse. This results in a false target at a fixed position up-range of the jammer platform as shown in Figure 3.

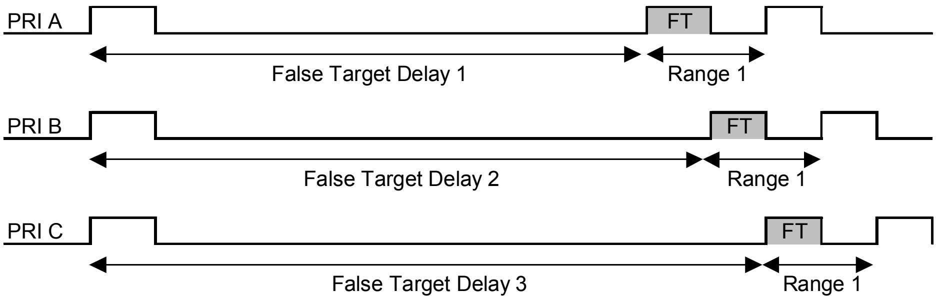

Figure 3: Up-Range False Targets with PRI Prediction

Predictions must be very accurate since in general the jammer will not be able to receive and transmit simultaneously. Hence, the PRI predictor may have to provide accurate timing information to the TG without any input to update its predictions for many PRI at a time. Even small errors in predicting the TOA of each pulse will rapidly accumulate over a large number of PRI.

Solving the pulse-to-pulse agile PRI prediction dilemma is no simple undertaking. It requires real-time pulse-to-pulse analysis, acquisition and tracking of patterns with minimal information, which is often corrupt (missing pulses and / or containing spurious pulses). Additionally, a good PRI prediction system must be able to acquire and monitor various PRI modulation types, which include constant, dwell-shift, linear-sliding (ramping), staggered or wobbulated (sinusoidal) modulations, and keep track of patterns through signal fades and receiver blanking. Moreover, this system is required to have a simple interface and be of a small form factor to facilitate the incorporation into DRFM or VCO based jammers. One last consideration is important to note. While it may be possible to use databases and look-up techniques in order to predict PRI patterns, this process is quite slow and prone to error in the database or changes in the patterns caused by "war modes" or other operating mode changes – true PRI prediction does not require any detailed information about the threat parameters.

How to Achieve PRI Prediction

Based on limited pulse train history the PRI Predictor determines the upcoming PRI value and thus the time of arrival (TOA) of the next radar pulse. As shown in formula 1 the prediction algorithms use PRI history to calculate the upcoming PRI. From that knowledge targets can be created at a programmable delay ahead of the arrival time, resulting in a leading false target. The process of prediction consists of pulse-to-pulse data acquisition, processing and output as shown in the flow chart in Figure 4.

$$PRI_{n+1} \sum_{k=m}^{n-1} W_k \times PRI_k$$

Formula 1: Prediction Formula

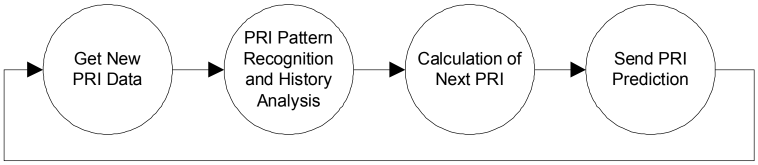

Figure 4: Algorithm Flow Chart

Using divide and conquer principles we have developed and implemented a number of algorithms, each trying to acquire and track a different type of PRI pattern. These prediction algorithms train themselves to recognize patterns using actual PRI values measured in real-time. They actively learn the characteristics of the input pattern and predict the upcoming PRI's. Each algorithm analyzes the same PRI data, but runs different prediction schemes and reviews only its own prediction history to monitor its performance. The PRI prediction software uses the Multiple Instructions Single Data (MISD) model, shown in Figure 5 below, to run the various algorithms in parallel. Since the system has a series of processes estimating the next PRI value, a prediction arbitrator is needed to choose which of the N predictions is most likely to be correct.

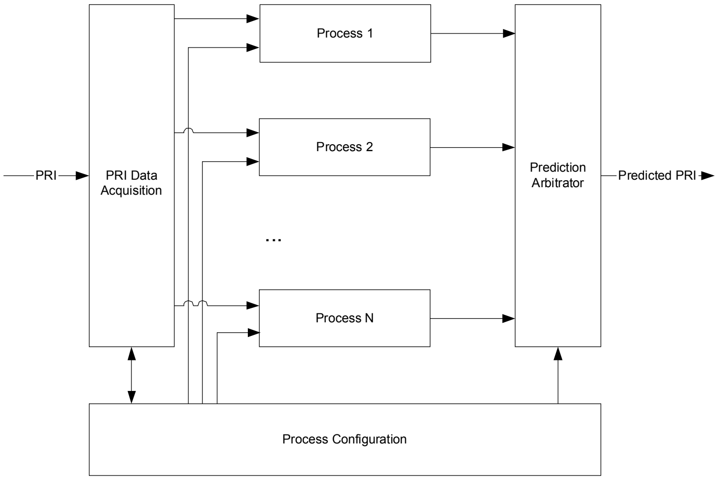

Figure 5: PRI Prediction Core Structure

The arbitrator uses a weighted probability function based on past accuracy and current state of the process to choose a prediction among the N available. This arbitrator must adapt quickly (pulse-to-pulse) in order to deal with the ever-changing state of the pulse train input and state of the various prediction processes. The "process configuration" block controls variables such as history length that the different processes will store and monitor. Shorter history monitoring can make acquisition and pattern lock faster, but it can result in false acquisition. The history length needed is very much PRI pattern dependent.

Once the PRI pattern is acquired and pattern tracking begins, the algorithms can keep tracking through periods of missing pulses and produce properly positioned target strobes during that time by keeping correct timing. The system assumes the prediction was right when the pulse does not occur in the expected time and keeps tracking the current pattern as if the pulse was present. Due to measurement and calculation errors, tracking through periods of missing data can only be done for a limited time to keep the technique and targets coherent. The ability to keep track through loss of signal is vital for systems where the receiver is blanked occasionally and for deceiving scanning radars. Of course, the PRI Predictor will perform better if it has actual data to base its predictions, hence receiver blanking should be minimized to improve PRI prediction.

The PRI Predictor is capable of filtering out some spurious pulses caused by interfering radar pulse trains and keep proper track of the current PRI pattern. This is done using time gating principles during track mode to eliminate pulses that arrive earlier than expected. Ignoring spurious pulses is important for PRI prediction since the PRI pattern can quickly loose its coherence and prediction accuracy can be affected. Also, by letting the Predictor control the DRFM writes, as well as the reads, the spurious pulses are not written into the memory to overwrite the current valid information and the deception technique will improve considerably since only valid RF data is stored and read out.

RF Prediction

Since RF agile patterns have forms similar to PRI agile patterns, we can use similar prediction principles as described above. Staggered or sliding RF agility can be predicted independently of PRI. One important difference in the sine algorithm implementation is that PRI information is required in order to predict the RF pattern. Once the time of arrival of the next pulse is predicted accurately, then we can attempt to predict its radio frequency.

Illustrated below is how a wobbulated RF agile pattern can be predicted. The RF change follows a sinusoidal curve which is sampled on each pulse. With sufficient history, the shape of the curve can be determined and from any given point on the curve, the next RF value can be calculated based on the TOA of the next pulse. For this reason it is necessary to predict the time of arrival of the upcoming pulse in order to predict its RF. RF wobbulation is typical of emitters making use of spin-tuned magnetron transmitters and appears as a random distribution since the individual RF values do not tend to repeat themselves (or possibly repeat with a very long period).

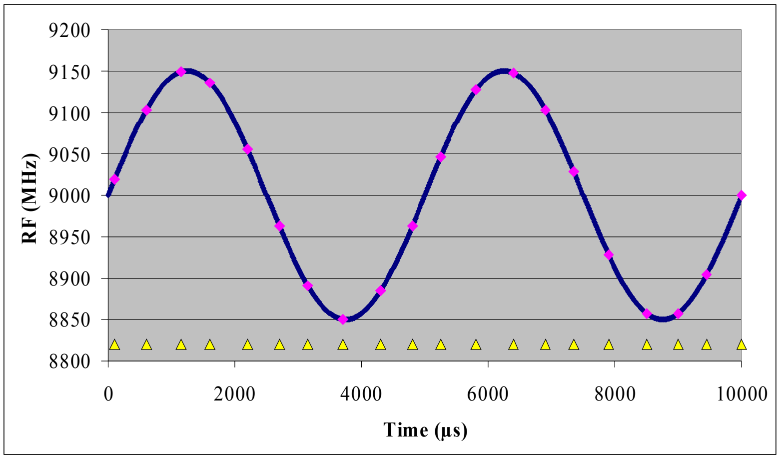

Figure 6: RF pattern illustration

A block diagram of the RF predictor is illustrated in Figure 7. Here a PRI predictor informs the RF Predictor when the next pulse is expected, enabling it to predict the RF. This type of system is ideal to control a VCO where the RF Prediction tunes the output and the false target position triggers a VCO output.

With RF prediction in addition to PRI prediction:

Figure 7 shows a system in which RF prediction and PRI prediction are controlling a fast tuning VCO to generate consistent up-range false targets. The RF prediction would command the VCO to switch frequency at the halfway point in the PRI, as shown in Figure 8. This gives a Techniques Generator an effective jamming range of ½-PRI up-range and ½-PRI down-range, which is a major improvement over down-range only capability without prediction.

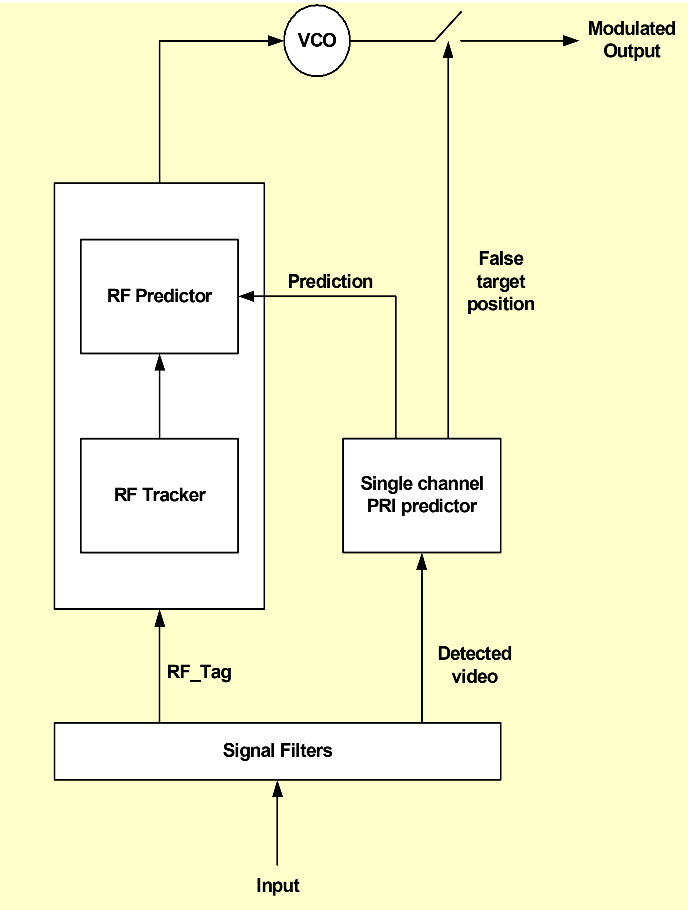

Figure 7: RF Agility Concept System

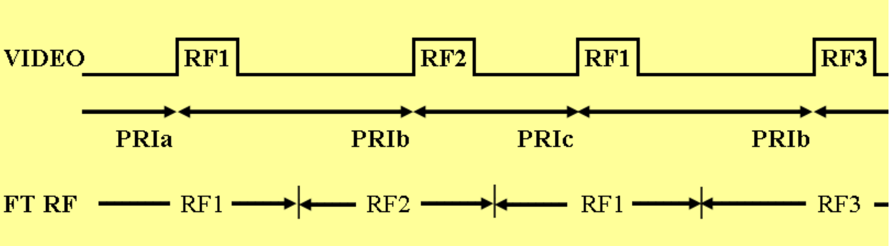

Figure 8: RF Agility Waveform

RF Agility Problem: Measurements

One key limitation of RF prediction is the accuracy of the RF measurements. Predicting the upcoming RF is a very complex process and predictions can only be as good as the measurements available. The better the measurement, the better the prediction. The more the measurement is affected by errors, the greater the error will be in the prediction. The main concern is that these RF measurement errors do not totally preclude prediction. Measurements from a DFD (digital frequency discriminator) or IFM (instant frequency measurement) suffer from errors and limited resolution. Often it is a tradeoff between measurement time and measurement precision. The advantage of prediction is that the measurement time can now take longer since RF and PRI predictions can be used to pre-trigger the jammer enabling better measurement accuracy by allowing more time for the measurement.

Presented in the following figures are accuracy results for RF prediction using a sine RF agile pattern with a mean RF of 9.1 GHz, deviation of 200 MHz, a cycle time of 100 ms and a mean PRI of 2.333 ms. The DFD measurement resolution is 1 MHz and we vary the error of the DFD to study its effect on prediction accuracy. We can see in Figure 9, 10 and 11 that the Prediction error is almost totally dependent on DFD error.

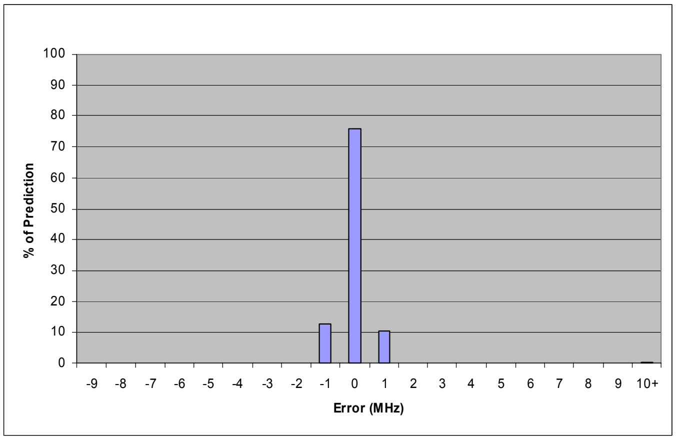

Figure 9: DFD Error = 0 MHz; 99% of Predictions are within 1 MHz

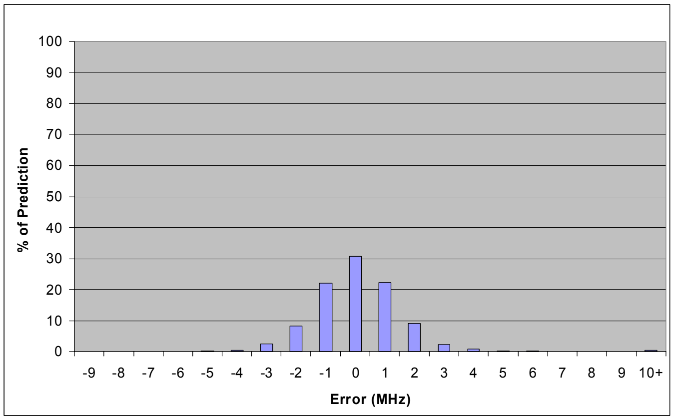

Figure 10: DFD Error = 1.5 MHz; 97% of Predictions are within 3 MHz

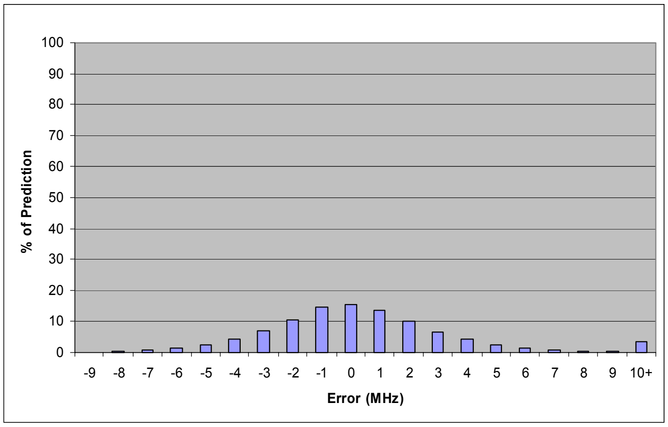

Figure 11: DFD Error = 3 MHz; 91% of Predictions are within 5 MHz

Prediction in a Complex Signal Environment

In an ideal case where there is a single in-band emitter, without dropped pulses or interfering pulses, a radar pattern can be acquired using little more than one complete frame of the PRI pattern. Unfortunately, this is seldom the case. Radar transmitters occasionally misfire, resulting in a small but not insignificant percentage of dropped pulses – typically 2-3 % for magnetron transmitters. There could also be several active emitters within the jammer's detection bandwidth, some of which should not be jammed (friendly radars, for example), and all pulse trains must be de-interleaved in real time so they can be addressed individually.

Accounting for Dropped and Interfering Pulses

PRI prediction can be used to provide feedback to add missing pulses or filter out interfering pulses and even de-interleave emitters. Once the radar PRI pattern is known a prediction system can use its knowledge in order to: first, account for dropped pulses by assuming a missing pulse when no event occurs at the expected time, thus keeping proper timing, and second, filter out interfering pulses since they will occur at a different time than expected. This is accomplished using a time filter controlled by the prediction as shown in Figure 12.

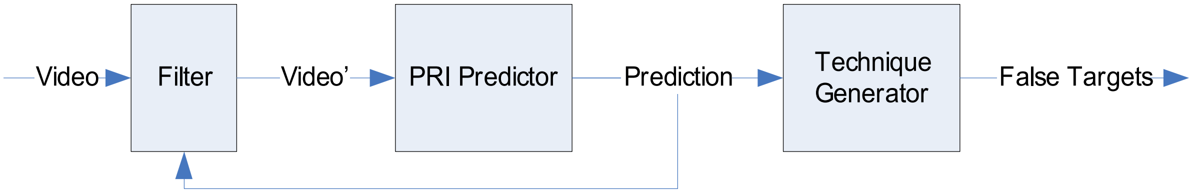

Figure 12: Using PRI Prediction to Filter Video.

The waveform in Figure 13 shows that by using expected time of arrival we can filter out interfering pulses and account for dropped ones.

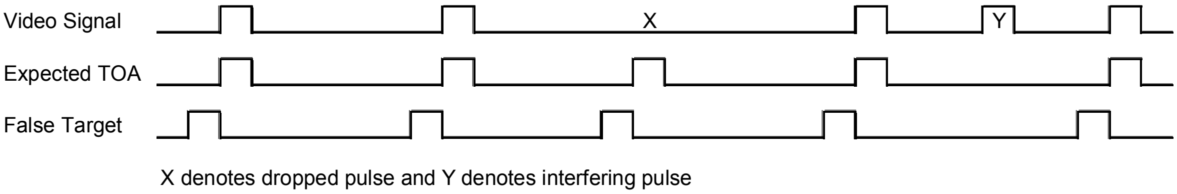

Figure 13: Waveform Showing A Dropped And An Interfering Pulse.

In order for a PRI prediction system to establish an accurate track and produce coherent false targets with high reliability, it is critical that dropped and interfering pulses be accounted for during acquisition. The problem is that during acquisition, expected time of arrival cannot be used to filter the waveform since the pattern is not yet tracked. Missing pulses can be accounted for using a few frames of the pattern during acquisition in order to find out which data was lost in certain frames. However, interfering pulses during acquisition must be filtered out using a discriminant such as radio frequency, pulse width or angle of arrival. If this information is not available or is unreliable, filtering interference to help acquisition can be difficult. However, if each emitter appears on its own for at least part of the time, long enough for the predictor to lock on to the pattern, the predictor can make use of the pattern to remove the interfering pulses in real time.

Real-Time De-interleaving of Emitters

Multiple in-band emitters pose a significant problem to a DRFM-based ECM system. Interleaved pulse trains will interrupt jamming each time the DRFM memory is overwritten with a new emitter signal. PRI prediction can help focus the ECM asset on one emitter, or even multiple emitters in parallel. Isolation of an emitter's pulse train is critical to efficiently jamming it.

The complex case depicted in Figure 14, shows the envelope of three emitters in band where emitter 1 is a non-scanner and emitters 2 are 3 and scanning through. The non-scanner might normally be the highest priority signal for the jammer, but each time one of the scanning emitters appears, jamming is interrupted since the PRI patterns are interleaved. It may well be that one or more of the scanners should be jammed as well, but without the ability to isolate each of the emitters, this may not be an option. These emitters need to be de-interleaved in order to properly identify the higher priority threat and jam it properly.

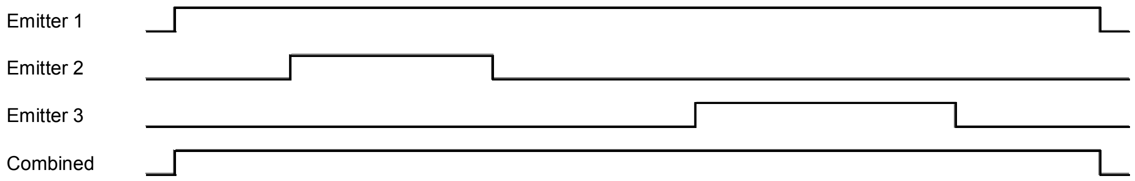

Figure 14: Envelop Of Three Emitters In Band

Using real-time de-interleaving of the pulses a system can effectively differentiate the various emitters and jam the highest priority threat whether it is one of the scanning emitters or the non-scanning emitter. There are several options for uniquely identifying each pulse to achieve pulse train de-interleaving: pulse width (PW); radio frequency (RF); angle of arrival (AOA); and expected time of arrival, which requires PRI prediction. The more information that is available to the predictor the easier it is to isolate the various pulse trains and track them individually, as shown in Figure 15.

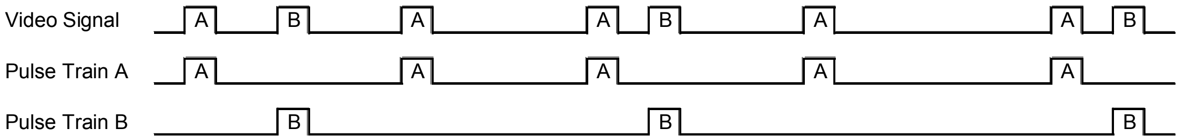

Figure 15: Interleaved Pulse Train With Discriminator.

Using RF, PW or AOA to Assist With De-interleaving

Radio frequency, pulse width and angle of arrival (AOA) can be useful in de-interleaving; however, such discriminator information is not always available or reliable. RF measurements from either a DFD or IFM may be available but not for some time after the pulse has been detected and written to the DRFM's memory, thus overwriting the previous contents. This problem can be overcome with RF delays or memory sharing schemes which may limit the DRFM's capability, but the measurements are not reliable in cases of pulse overlaps. Pulse width is easily measured and is readily available, but it is sensitive to pulse overlaps and detection threshold level. Care must be taken to retain amplitude information so that PW can be measured at a consistent level, eg, -3 dB point. Angle of arrival can be used as well, if it is available, but there are many scenarios where this would not be a useful discriminant, such as multiple ship-board radars active on the same ship, or a SAM site with multiple associated emitters in the same general location. However, there are instances where AOA could be used effectively, especially in air-to-air engagements.

Using PRI Prediction for De-interleaving

PRI Prediction gives us a key piece of information needed in de-interleaving: expected time of arrival of the next pulse for the tracked pulse train. Using this information we can assume that pulses which are not expected are from a different emitter. Illustrated in Figure 16 is how two pulse trains can be de-interleaved based on expected time of arrival.

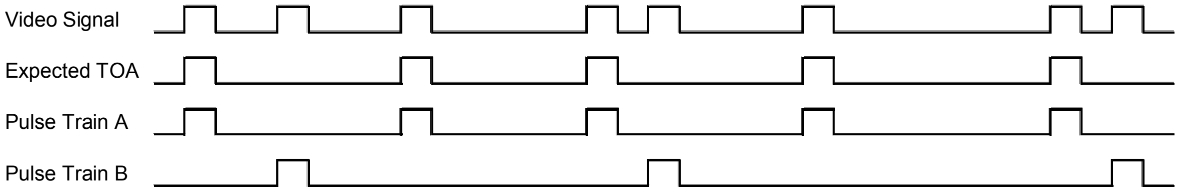

Figure 16: De-Interleaving Based On Expected Time Of Arrival

The main issue with time of arrival filtering is that the prediction system must be tracking each of the interleaved patterns; this means it needs to see only one new emitter at a time, at least long enough to establish a proper track. For this reason a combination of expected time of arrival and some other form of pulse identification is preferable, especially during the pattern acquisition phase.

Returning to the example above (Figure 14); in order to de-interleave and track emitters 2 and 3, the system must track emitter 1 first. This creates a need for multiple parallel prediction channels. While one of the predictors is tracking emitter 1 in order to filter it from the other channels, the other predictors can focus on acquiring and tracking emitters 2 and 3 as they pass through.

Another advantage of having multiple parallel prediction paths is that it is now possible to retain information and quickly reacquire the pattern on each illumination of a scanning emitter, assuming the radar pattern has not changed from the last illumination. This enables the ECM system to jam a larger part of the illumination as fast reacquisition can be performed with only a few radar pulses.

Using a Combination for De-interleaving

A combination of one or more of RF, PW and AOA with time de-interleaving is ideal since the discrimination information will help to de-interleave the pulse trains during the acquisition phase, then once tracking begins the time filtering can be used to isolate the emitters based on time of arrival. However, if it is assumed that each signal will appear on its own at some point, time based de-interleaving on its own can be very effective.

Building on our filtering system we can have multiple parallel predictors controlling a de-interleaving scheme, as shown in Figure 17. The prediction used by the technique generator can be selected based on information such as signal activity, threat identification and its relative priority.

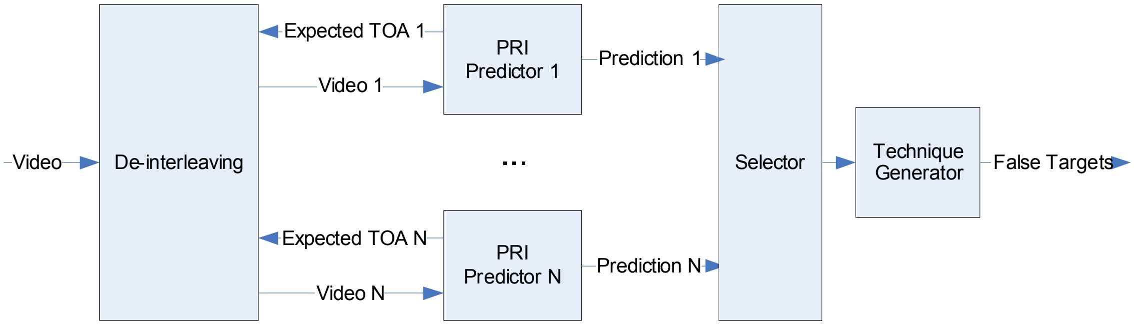

Figure 17: Parallel Prediction Paths For De-Interleaving

RF Agility Problem: Multi-Signal Environment

When multiple signals are present within the jammer's current RF band, we must isolate the RF agile emitters from the constant RF emitters meaning that RF can no longer be used to de-interleave unless their RF ranges are distinct enough. However, when another signal is also present within the same band it becomes difficult to sort the signals and isolate the agile signal. Information like angle of arrival could help but is often not available. Real time pulse train de-interleaving based solely on predicted time of arrival of pulses has provided the necessary breakthrough; by first predicting the time of arrival and using this knowledge, the RF information can be sorted.

Example of Multiple Emitters in Band

The sample environment described in Figure 18, a typical environment is illustrated where each emitter is in the same band. Without de-interleaving, a jamming system will suffer greatly since scan overlaps occur approximately 25 percent of the time for each emitter.

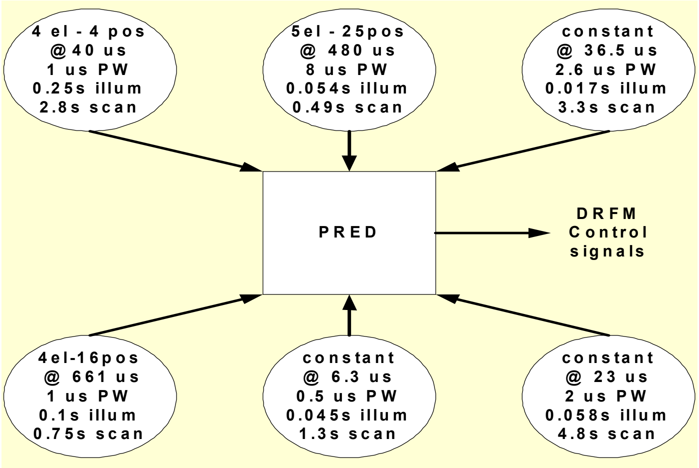

Figure 18: Environment Characteristics

With real-time de-interleaving, the prediction accuracy, shown in Figure 19, is almost independent of illumination overlaps when selecting one signal at a time to respond to (or responding to them in parallel with multiple DRFMs). This shows that real-time de-interleaving will greatly improve the ECM capability. We notice that the Predictor Effectiveness is a bit lower against emitter 1 and 2 but that is because they are more complex staggers with very limited number of PRI per illumination.

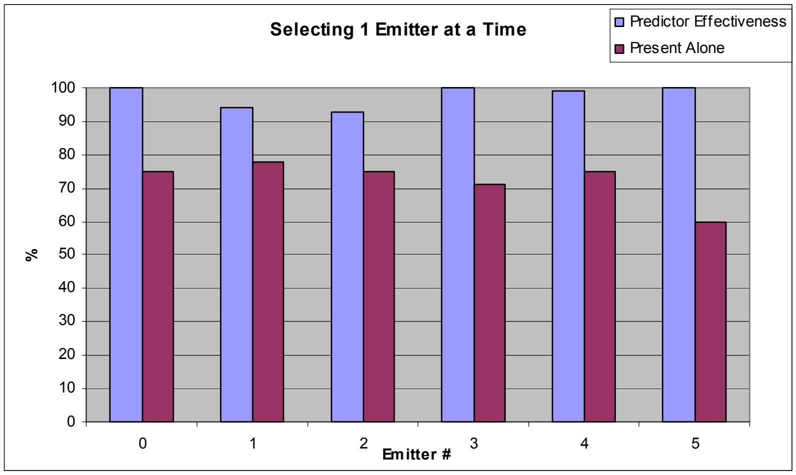

Figure 19: Predictor Effectiveness when Selecting One Emitter at a Time

Applications of PRI Prediction

There are many applications beyond up-range targets for PRI and RF prediction such as improved control of a single Tx/Rx antenna, better use of a single ECM asset, enhanced ECM techniques and lower power consumption.

Controlling the Receiver/Transmitter

It is important to optimize receive and transmit times of an ECM system that cannot perform simultaneous transmit and receive. The system should receive as many pulses of the emitter as it can while it is transmitting in between pulses; i.e., non-coverpulse techniques. Using PRI prediction, a system can receive only when the next pulse is expected, as illustrated in Figure 20. This makes it possible to refresh the predictor and the DRFM so that PRI pattern changes can be quickly recognized and the DRFM memory contents are current.

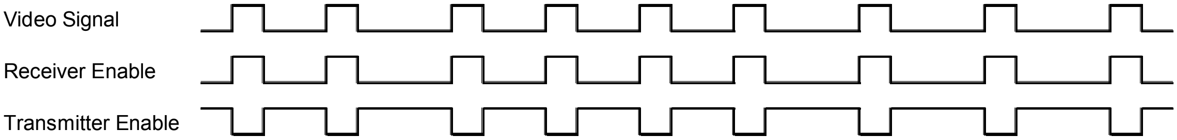

Figure 20: Receiving Every Pulse With Non-Coverpulse Techniques

For coverpulse techniques, however, it is necessary for the jammer to transmit a signal to coincide with the pulses arriving at the jammer antenna. In this case, it is necessary to mask the receiver for several pulses at a time, with only periodic look-throughs at the expected time of arrival of the radar pulse. This requires very accurate prediction so that the radar pulse is actually within the expected receive window. Figure 21 illustrates a simple example of receiving every fourth pulse, although the blanking period might typically cover a much larger number of pulses. In this example, an error of one clock cycle in the prediction of the TOA of each pulse could result in an error of 4 clock cycles in the expected TOA for each fourth pulse. If the look-through was only allowed on every 100 pulses, the error could be prohibitive unless the prediction is done such that errors tend to average out over a large number of pulses. This is done by measuring the total time interval between large numbers of pulses, ideally multiples of the pattern frame length.

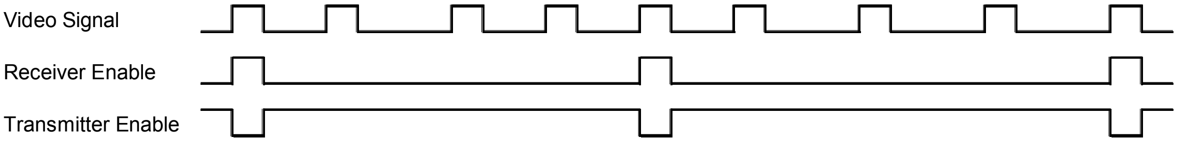

Figure 21: Receiving Every Fourth Pulse

Controlling a Single ECM Asset

Using a multi channel PRI predictor system, as illustrated below, it is simple to control a single ECM asset such as a DRFM. The predictor has simple timeshare functions to select automatically a single signal to write in the DRFM and jam. Signals can be validated based on PRI range, PW range and scanning status, as well as RF range.

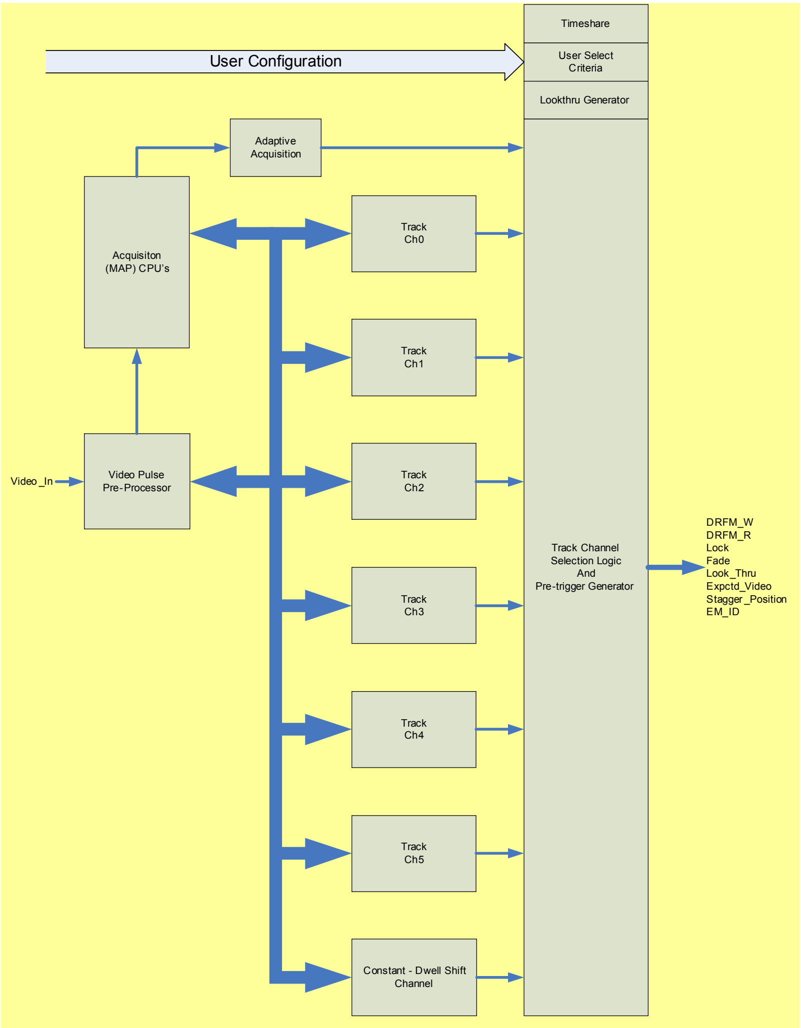

Figure 21: Block Diagram of Multi Channel Predictor

The Predictor can be configured to switch the output automatically on valid signals. This allows the use of a single DRFM to jam multiple scanning radars simultaneously. When more than one valid signal is present the timeshare algorithm calculates optimal allocation based on signal present, predictor accuracy, first come first served and scan priority. This is particularly useful against weapon systems that use separate acquisition (scanning) and tracking (non-scan) radars. The acquisition radar can be dealt with as it passes through, then once it is gone focus can return to the tracking radar.

Shown below are two sets of results where the Predictor timeshares the ECM asset between various emitters, in the same environment as described above. Figure 22 shows the predictor trying to jam all 6 emitters. When emitters are alone they are selected and when more than one is present only one is selected on a first come first served basis. In Figure 23, emitters 4 and 5 are set to be non-jam emitters and thus are never selected. In both figures, emitter 0 seems to be jammed more. This is due to the fact that it has the longest illumination time and thus it is more likely to be there first.

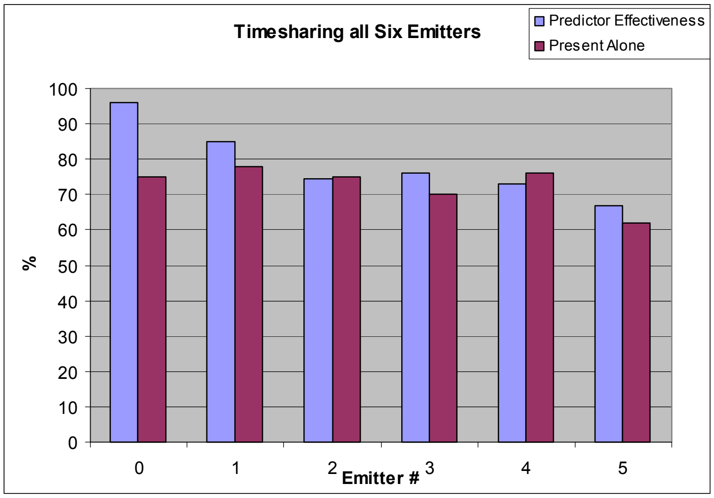

Figure 22: Timesharing All Six Emitters

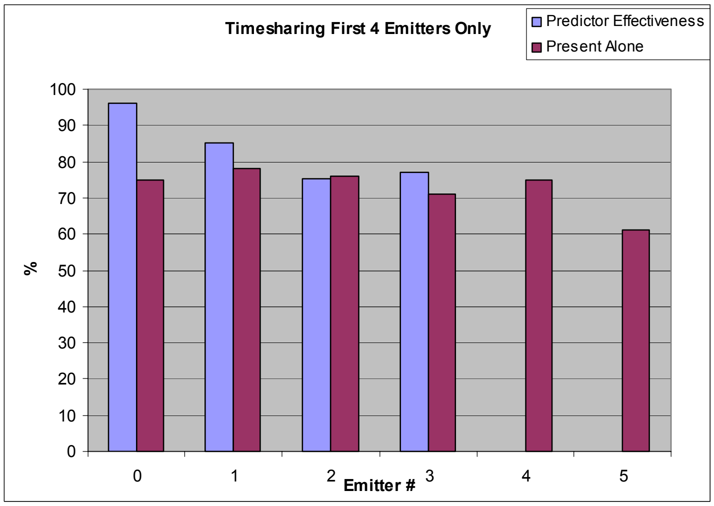

Figure 23: Timesharing First 4 Emitters Only

ECM Techniques

The main application for PRI Prediction is up-range or in-bound targets. It allows technique generators to produce range gate pull in (RGPI) techniques, where the false target moves in-bound. In addition, PRI Prediction can enable the techniques generator to pull its targets past multiple PRI's up-range and down-range effectively extending the target range capability well beyond a single PRI.

Range Bin Masking (RBM) techniques can be greatly enhanced using prediction. Instead of using head to tail principals where the pulse width is repeated, triggered from video, it can be triggered at the PRI's midway point to make the returns coherent both up-range and down-range, thus RBM becomes Coherent RBM (CRBM).

Lower Power Consumption

With PRI Prediction an ECM system gets smarter control of its assets which results in lower power requirements. Coherent deceptive jamming requires less radiated power than noise jamming. In addition, when the false targets are positioned up-range precisely, in order to make them correlate, the ECM is more effective, even with lower power levels. This smarter control by PRI prediction makes it perfect for economical jamming systems and unmanned aerial vehicles (UAV) ECM applications.

ESM / RWR Applications

Apart from being a useful add-on to ECM systems, PRI Prediction can also help electronic support measures (ESM) and radar warning receivers (RWR) systems. By de-interleaving the emitter pulse trains in real-time the process of identifying the various threats can be much faster since the system can focus on a single emitter at a time. Pulse train de-interleaving is normally very processor intensive and is done off-line over a period of seconds.

A multi-channel predictor, with six or more parallel channels, would be a particularly good addition to an ESM system that is being used to control a jammer system. The jammer cannot afford to wait several seconds to start jamming a signal that might no longer be there. A predictor system would allow the system to focus on one pulse train at a time to identify the emitters considerably faster. A Predictor system could also be useful to filter out some of the simple or known emitters in band to help the ESM system process the unknown emitters.

Adding PRI Prediction to an Existing Jammer

Adding PRI prediction to an existing ECM system in order to increase its false target capability is fairly simple, as shown in Figure 24. PRI Prediction can complement a Technique Generator by providing it with predictions, allowing the TG to produce up-range techniques. The Predictor itself can be as small as a single Field Programmable Gate Array (FPGA) integrated circuit and designed into one of the jammer's PC boards.

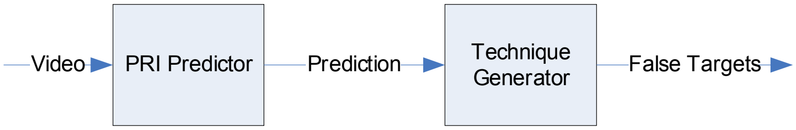

Figure 24: Integration of PRI Prediction with a Technique Generator

The PRI predictor system developed by MC Countermeasures Inc. is implemented using a single Altera Stratix II FPGA, Figure 25. FPGA devices are chosen since they facilitate customization which is vital since every ECM application or system is unique. With approximately 1.5 million logic gates, 50 thousand registers and 2.5 Mbits of memory the Stratix II device, EP2S60, enables the predictor to have flexible and powerful logic with soft core processors, state-machines and combination logic to perform its tasks of enhancing any ECM system.

Figure 25: PRI Prediction Device (33mm x 33mm)

Conclusion

In short, PRI and RF Prediction are the key to maximizing ECM effectiveness in a dense environment. With careful design, a PRI predictor can overcome many real world problems which a coherent jammer must address: multiple interleaved in-band emitters, both friend and foe; dropped or missing pulses due to scanning radar modes or transmitter misfire; and insufficient isolation in the jammer system for simultaneous receive and transmit operation.

Acknowledgements:

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