An Investigation of the Trade-offs Between Electronic Protection and Processing Efficiency in a Multistatic Noise Radar Network

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Abstract—The Air Force Institute of Technology (AFIT) has developed an experimental multistatic ultrawideband (UWB) random noise (RN) radar to produce highly accurate, highly resolved imagery. Recent experimental studies have shown sub-meter range resolution performance. A focus of current research is the reduction of signal processing and network latency in multistatic range calculations, while maintaining a high level of electronic protection (EP). Investigated here is the development and application of a software model to accelerate exploration of new concepts in support of this research. The software model, developed using Simulink®, was verified component-by-component and as a whole with both theoretical and measured performance of the UWB-RN radar hardware. The Simulink® model was then applied to qualitatively analyze the EP performance of known pseudorandom template play-back strategies as compared to traditional RN waveforms. Key to this concept is the fact these templates are captured from a thermal noise source and are therefore truly wide-sense stationary, uncorrelated waveforms. The analysis reveals that properly designed pseudorandom templates provide an equivalent level of EP and may provide up to a 75% increase in multistatic processing efficiency.

I. INTRODUCTION

Ultrawideband (UWB) random noise (RN) is often described as a featureless waveform, and therefore has excellent electronic protection (EP) properties [1]–[3]. When applied to radar waveforms, the wide fractional bandwidth can also provide high fidelity in target localization. Previous research has shown that uncomplicated UWB-RN radar nodes configured for monostatic/multistatic operation can produce highly accurate, highly resolved sub-meter imagery of target scenes while preserving EP characteristics [3], [4]. A major thrust of our current research is focused on enhancing the multistatic signal processing architecture to reduce the negative effects of network latency and centralized signal processing. Bistatic digital signal processing (DSP) involving a cluster of displaced radar nodes requires data transfer over a throughput limited data link. Unlike deterministic signals, stochastic implementations require transmit and receive signals be passed over a network a posteriori for each bistatic channel in the multistatic environment. AFIT’s current design performs monostatic DSP locally at each node (distributed) and bistatic DSP centrally at the cluster head, as such the transmit signal, receive signal and monostatic DSP results of each node are continuously transferred over the data link. This can strain the network and introduce latency into an already time sensitive process. A priori knowledge of each node’s transmit waveform can reduce the amount of traffic traversing the network and push the bistatic DSP burden back to each node. Development of transmit templates is one method to provide a priori knowledge of the stochastic transmit signals; however, loss of EP characteristics and lower signal-to-noise ratio in cross-power spectral densities are two main areas of concern. By creating a random sequence of many different transmit templates of varying length and order, it may be possible to mitigate these effects. Key to this concept is the fact these templates are captured from a thermal noise source and are therefore truly wide-sense stationary, uncorrelated waveforms.

II. SYSTEM DESCRIPTION

The AFIT noise network (NoNET) is an experimental monostatic/multistatic UWB-RN radar developed to produce highly accurate, highly resolved imagery of a target scene while maintaining a simple design. A block diagram of the AFIT NoNET is shown in Fig. 1. A thermal noise source generates a waveform that has a Gaussian amplitude distribution and a uniform frequency distribution in the 0–1.62 GHz frequency band. For signal processing and waveform
conditioning, a bandpass filter is implemented to band-limit the waveform to 350–750 MHz. The bandpass filter half-power cutoff frequencies are directly related to the antenna bandwidth and analog-to-digital (A/D) conversion sampling rate. Before transmission, the waveform is then passed through a power splitter. One output is sent directly to a wideband log-periodic transmit antenna. The other output is sent to the Direct-Conversion receiver (DCR) and then stored as the reference waveform. Reflected energy is captured by a second co-located wideband log-periodic antenna. The receive channel is also band-limited to 350–750 MHz and then amplified. The resulting waveform is then passed to the DCR for DSP.

A DCR, rather than a super-heterodyne, architecture is used to avoid complexity in the receiver while maximizing flexibility in the receiver processor. As such, the NoNET receiver architecture does not use I/Q channels typically found in coherent receivers. Both analog channels are converted to digital format at 1.5 GSa/s, satisfying Nyquist anti-aliasing limitations in the 0–750 MHz spectral band. The output of the A/D process is ported to a Matlab® environment, where monostatic range estimation is accomplished by digital cross-correlation. When operating in a multistatic configuration, each remote node performs monostatic DSP and then sends the results to a central node. In addition, the transmit and receive digital waveforms at each node are sent to the central node for DSP of each bistatic channel.

III. BACKGROUND

A qualitative analysis of EP properties is performed by investigating how well template play-back strategies maintain the featureless nature of UWB-RN, where quadrature mirror filter bank (QMFB) and cyclostationary spectral (CSS) algorithms are used to extract potential waveform features. This section briefly describes those signal processing techniques.

A. Quadrature Mirror Filter Bank Analysis

Quadrature mirror filter bank analysis implements orthogonal wavelet basis functions and the wavelet transform to divide the time-frequency plane into tiles, where a tile is a rectangular region of the time-frequency plane containing most of the basis function energy [3], [5]. The basis functions decompose the signal into tiles of the same size by using consecutive wavelet filter pairs (i.e. highpass and lowpass) with re-sampling to split the signal into frequency bands. The result is series of time-frequency layers, where each layer is a resolution trade-off in time and frequency. Fig. 2(a) illustrates the QMFB process and resulting layers at each of the consecutive wavelet filter pair decompositions. Filters $G$ and $H$ correspond to the high and lowpass filters, respectively. All input signals are zero padded such that the resulting signal length, $N_p$, is a power of 2, where the number of layers, $L$, is related to signal length by $N_p = 2^L$. The frequency and time resolution of layer $l$ is given by [3]

$$f_{res} = \frac{f_s}{2(2^l - 1)} \quad (1)$$

$$t_{res} = \frac{N_p}{f_s (2^L - t - 1)} \quad (2)$$

where $f_s$ is the sample frequency. Analysis of the proper layers can provide extraction of signal features such as bandwidth, center frequency, energy distribution, modulation type, code periods and signal duration. As shown in Fig. 2(b) and Fig. 2(c), QMFB processing of a hybrid frequency shift keying/phase shift keying (FSK/PSK) modulated signal allows estimation of all modulation parameters. Layer 7 shows the FSK modulation and resulting Costas sequence; whereas, the higher time resolution of layer 4 shows the timing information of both the FSK subcode period and PSK Barker sequence.

B. Cyclostationary Spectral Analysis

Cyclostationary spectral analysis is a bi-frequency spectral analysis technique, where a signal is modeled as a cyclostationary process rather than a stationary process. A process is said to be cyclostationary if its autocorrelation is a periodic function of time [6]. The cyclic autocorrelation of a signal $s(t)$ is defined by [7]

$$R_s^c(\tau) \triangleq \lim_{T \to \infty} \frac{1}{T} \int_{-T/2}^{T/2} x(t + \tau) x^*(t - \frac{T}{2}) e^{-j2\pi \nu t} dt, \quad (3)$$
where $T$ is the signal duration, $\alpha$ is the cycle frequency and $\tau$ is some time delay. The signal $s(t)$ is cyclostationary if $R^x_\alpha(\tau)$ does not equal zero at some $\tau$ and some $\alpha \neq 0$. Furthermore, the set $\{\alpha : R^x_\alpha(\tau) \neq 0\}$ is referred to as the set of cycle frequencies. Similar to the PSD, the cyclic spectral density (CSD) is the Fourier transform of cyclic autocorrelation function [3]:

$$S_x^a(f) = \int_{-\infty}^{\infty} R^x_\alpha(\tau)e^{-j2\pi f \tau} d\tau.$$  \hspace{1cm} (4)

For signals of finite duration $T$, the estimated CSD becomes [6]

$$S_x^a(f) \approx S^{a}_{T_w}(t,f)T = \frac{1}{T} \int_{-T/2}^{+T/2} S^{a}_{T_w}(u,f)du,$$  \hspace{1cm} (5)

where $S^{a}_{T_w}(u,f)$ is computed using overlapping short-time fast Fourier transforms with window size $T_w$. Fig. 3 illustrates how hybrid FSK/PSK signal features can be extracted from the CSD. By examining the correct centroids almost all features of the hybrid modulation can be extracted. Fig. 3(b) identifies the Costas frequency array (no timing information) and modulation bandwidth. A closer look in Fig. 3(c) allows extraction of the FSK subcode period and PSK Barker sequence bit duration. One disadvantage of using only the CSS analysis of the FSK/PSK signal is the lack of time-frequency information provided in the QMFB process, where the QMFB processing allowed extraction of the Costas sequence timing.

### IV. METHODOLOGY

#### A. Development and Verification of the Software Model

The intent of the software model is to accurately emulate the expected behavior of the AFIT NoNET hardware, and was developed using Simulink®. A subsystem for each hardware component was developed independently to match its measured response, then all subsystems were combined to achieve the desired system response. With DSP routines already developed for the Matlab® environment, only the RF front end and A/D board are modeled in Simulink®. A top-level illustration of the full software model is shown in Fig. 4.

The AFIT NoNET transmit waveform is produced using a solid state thermal noise generator, where a Gaussian distributed random number function block is used in Simulink® to model the noise source. The power of the generated signal is controlled by adjusting the variance of the random number, and the bandwidth is controlled by adjusting the time between samples, $T_s$. The thermal noise source transmits at -85 dBm/Hz (variance is 0.010) and has a half-power bandwidth of 1.62 GHz. The minimum sampling period is calculated using $T_s = 0.5*f_{\text{max}}$. As a result the sample period in the software model was set to 250 ps, producing a uniform PSD up to 2.0 GHz. A low-pass filter was implemented to achieve the roll-off effect at 1.62 GHz.

Using the low-pass and high-pass filter function blocks in Simulink®, a bandpass filter was developed to match the half-power spectral band of the actual system. The high-pass and low-pass filter blocks in this model are designed as Chebyshev finite impulse response filters with stopband edges of 350 MHz and 730 MHz, respectively. The Parks-McClellan (a.k.a Equiripple) algorithm is used to determine the optimal Chebyshev filter coefficients, with a constrained passband ripple of 0.001 dB and stopband attenuation of 40 dB. These parameters were chosen to best match the low passband ripple, high stopband attenuation and passband spectral response of the actual hardware. The peak PSD at the output of the simulated bandpass filters matches well to the measured hardware response, and the half-power bandwidth (BW) of the simulated transmit channel deviates by less than two percent.

Implementation of the power divider and low noise amplifier (LNA) are straight forward. The simulated power divider replicates the input signal and applies a power gain of -3.62 dB to both signals. The power at each output of the divider is less than half the input to account for insertion losses. The LNA block on the receive channel is a sample-by-sample multiplication of the input signal by 20 dB. This gain matches the hardware response.

Although the AFIT NoNET system uses wideband log-periodic antennas on the transmit and receive channels, currently this software model assumes ideal isotropic radiators. It is a straight forward task to implement the antenna transfer
function and not necessary for the investigation described in this paper.

The software model has a subsystem to represent the transmit waveform interaction with the environment, where subsystem accounts for free space path loss, radar cross section (RCS), and target range and velocity. Although the transmit signal is UWB, the environment subsystem currently assumes a narrowband signal centered on the UWB-RN mean frequency. Development is ongoing to capture the necessary wideband phenomena. Additionally, multiple targets can be introduced to simulate multi-path effects.

A variable delay block for the reference signal allows calibration of the software model. For instance, the default delay is set to 13.68 ps to account for propagation of the received signal through receive channel circuitry (i.e. BPF and LNA). Re-calibration is required to simulate additional hardware configurations.

The last function of the Simulink model is to send the transmit channel reference signal and receive channel signal to the Matlab workspace for monostatic DSP and detection and estimation processing. A Direct Conversion Receiver subfunction block samples the send and receive channels at a user-defined rate, where the default is 1.5 GSa/s to match the A/D board. The two sets of samples are then ported to the Matlab workspace for interpolation to achieve a synthetic sample rate of 6.0 GSa/s.

**B. Template Play-back Experiment**

The feasibility of pseudorandom template play-back strategies is evaluated from two perspectives; how well the pseudorandom waveform preserves the EP properties of UWB-RN and quantifying the potential multistatic processing efficiency improvements.

1) *Preservation of Electronic Protection Properties:* Using an 8-bit A/D conversion board, a digital copy of the AFIT NoNET noise waveform is captured to implement two play-back strategies. The captured waveform is then divided into templates of length $T_T$. The first waveform design is a periodic replay of a single template, where the transmit signal is given by $s_t(t) = \{T_1, T_1, T_1, \ldots, T_1\}$. On the other hand, the second strategy implements a random (uniformly distributed) sequence of $N_T$ templates, where one realization of a transmit signal generated for $N_T = 5$ is given by $s_t(t) = \{T_1, T_2, T_3, \ldots, T_4, T_5, T_2\}$. This play-back strategy represents the middle-ground between the first strategy and a true UWB-RN waveform. Each template play-back strategy will be replayed using the software model transmit channel, where the AFIT NoNET receiver signal processing algorithms are replaced by the QMFB and CSS algorithms. The EP performance of each design, to include true UWB-RN, was analyzed for signal-to-noise plus interference ratios (SNIR) of $\{\infty, 0, -4, -14\}$ dB. Furthermore, the template length $T_T$ and $N_T$ were also varied to identify design parameters that affect the EP properties. Ultimately the inability to extract waveform features using QMFB and CSS analysis discriminates good EP from bad EP properties.

2) *Processing Efficiency:* The primary objective of the processing efficiency experiment is to quantify the potential AFIT NoNET processing gains achievable with template play-back strategies. For the experiment, an ad hoc wireless network (802.11g) is setup for communication between the displaced radar nodes. The correlation period is set to 1$\mu$s with an A/D sample rate of 6 GSa/s, which results in signals of 6000 double-precision samples in length. Under the current AFIT NoNET signal processing architecture, if $N_{avg}$ cross-correlation are averaged, each remote node must send $N_{avg}$ reference and receive signals and a single monostatic DSP result of 6000 samples. As an example, when $N_{avg} = 40$ the total number of double-precision data samples sent over the network is 486000 per remote node. The central node is then required to compute the 20 remaining bi-static channel cross-correlations, perform data fusion and plot the 2-dimension target scene. The process is then repeated for each subsequent measurement of the target scene. If each radar node has a priori knowledge of all transmit waveforms, they can calculate both their monostatic and bistatic channels correlations. Using this signal processing architecture, the remote nodes only have to send their monostatic and bistatic DSP results to the central node for data fusion and plotting. Not only does this better distribute the correlation processing burden, but also reduces the network burden. Both architectures are examined by capturing network latency and DSP latency statistics for clusters of 1-4 remote nodes averaging 1, 10, 20 and 40 correlations.

**V. RESULTS**

**A. Electronic Protection Results**

A subset of the QMFB and CSS analysis results are presented in Fig. 5. As expected, the UWB-RN iterations indicate that the current AFIT NoNET waveform exhibits properties consistent with a featureless waveform. Furthermore, with its low transmit power (-85 dBm/Hz) the EP performance improves in a contested RF environment. Figs. 5(a) and Fig. 5(d) illustrates the significant increase in EP when the SNIR is at or below -4 dB, where cross-correlation processing was still able to accurately detect and estimate target range.

When the transmit waveform is developed from a single template, the play-back strategy introduces waveform features and reduces the EP of the radar. As illustrated in Fig. 5(b)
and Fig. 5(e), the periodicity of the waveform is identifiable in poor SNIR conditions. A more in depth analysis of the spectral content of each template suggested $T_T$ as a key design parameter for a periodic replay of one template. Recalling that the instantaneous frequency of WGN is a uniformly distributed random process, $T_T$ less than $0.1 \mu s$ does not provide enough time to uniformly “fill” the spectrum. It can also be shown that the range resolution is inversely proportional to bandwidth; therefore, a template length that provides sufficient time to uniformly fill the spectrum is a requirement to maintain high range resolution.

A pseudorandom play-back of many different RN templates shows the potential to provide a similar level of EP as compared to the true UWB-RN waveform, and is shown in Fig. 5(c) and Fig. 5(f). The exception is a small value for $N_T$. If the random indexing sequence is uniformly distributed between 0 and $N_T$, then randomly re-ordering a set of $N_T$ RN templates approaches a truly random noise waveform as $N_T$ increases. Furthermore, under the assumption that the random indexing integer is uniformly distributed, the mean frequency at which a template is expected to repeat is $1/N_T T_T$ Hz. This result highlights a second parameter for consideration when designing template-based play-back strategies, where better EP is achieved as $N_T$ and/or $T_T$ increases.

**B. Processing Efficiency Results**

When operating in multistatic mode, the AFIT NoNET cluster of nodes communicate over an IEEE 802.11g ad hoc wireless network; however, the following analysis of results is not intend to explain the inter-workings of the communication standard and detail why a particular multistatic architecture experienced a given network latency. Instead, the following discussion attempts to remain neutral of the specific wireless network implementation, where the expected performance of the network can be predominantly evaluated by its limiting capacity (throughput), data payload size, number of active nodes and the frequency at which those nodes access to the network. Regarding payload, each double precision data point in Matlab® is 64 bits in length and each 6000 sample waveform is 0.3662 Mbits in length; therefore, the total number of megabits, $N_{Mb}$, transferred over the network to compute one multistatic target scene measurement is determined by

\[
\text{Arch 1: } N_{Mb} = N_{rnode} (2N_{avg} + 1) \times 0.3662
\]

(6)

\[
\text{Arch 2: } N_{Mb} = N_{rnode} (N_{rnode} + 1) \times 0.3662,
\]

(7)

where $N_{rnode}$ is the number of participating remote nodes, and $N_{avg}$ is the number of cross-correlations averaged. These
metrics, along with network latency and mean DSP time, are the fundamental metrics used to quantify the performance of each architecture.

Table I shows the 3 and 4 remote node results for each architecture. As expected, the mean network latency and central node DSP burden increases as the $N_{rnode}$ and $N_{avg}$ increase for architectures 1; whereas, the remote node monostatic DSP burden only increases as $N_{avg}$ increases. Additionally, architecture 1 has an increasing latency variance, where the variance gives insight into the stability of the network. On the other hand, architecture 2 provides approximately the same mean latency and variance for all $N_{rnode}$ and $N_{avg}$ and implies more network stability. With one exception, architecture 2 shows better mean latency and network stability for all configurations. The exception occurs when only one cross-correlation is used to measure the scene. This results from the increased $N_{Mlb}$ of architecture 2 compared to architectures 1, where $N_{Mlb}$ for 4 remote nodes is 4.4 Mbits and 7.3 Mbits, respectively.

While architecture 2 increases the remote node DSP burden, the central node DSP burden is much less as compared to architecture 1. As shown in Fig. 6, the fully distributed DSP method implemented in architecture 2, along with the reduced network load, provided the best system stability and best expected multistatic target scene update rate when cross-correlation averaging is implemented. Ideally, the remote nodes should update the central node at a rate equal (or faster) to the central node’s imaging update rate.

VI. CONCLUSIONS

An analysis of template play-back strategies confirmed the predicted signal processing gains achievable when a priori knowledge of UWB-RN transmit waveforms is available. Furthermore, the analysis identified a potential pseudorandom play-back strategy and key design parameters that provide comparable EP properties as compared to traditional UWB-RN waveforms. These findings support the incorporation of high-speed digital-to-analog (DAC) converters in the AFIT NoNET radar to validate the simulated results and to evaluate any degradation of target estimation performance resulting from implementation of template play-back strategies using DACs.

REFERENCES