THE NEXT-GENERATION SUPERCONDUCTOR-ENHANCED SPECTRUM MANAGEMENT & UTILIZATION
-- A QUANTUM INCREASE IN PERFORMANCE AND QUANTUM REDUCTION IN COST

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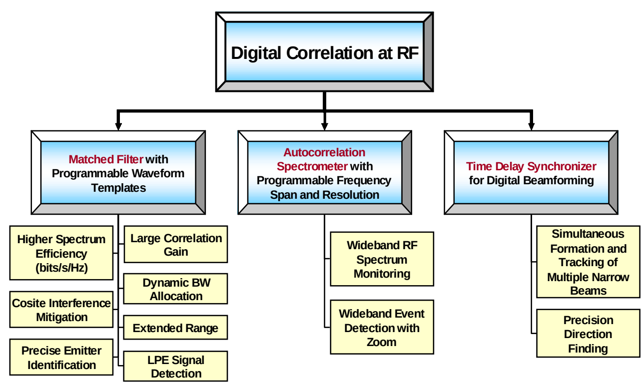
ABSTRACT

A major fundamental issue for all of DOD high capacity (HC3) wireless communications is spectrum management and utilization. HYPRES Superconductor MicroElectronics offers the potential for robustly accomplishing this critical requirement in a manner uniquely superior to conventional electronics in every aspect – performance, SWaP, and cost to implement, and extendable to the combined communications and signals intelligence (SIGINT) needs. This paper addresses the transformation of DoD capabilities by enabling a paradigm change in the implementation of the three key functions (spectrum monitoring, spectrum control, and spectrum utilization) -- enabling dynamic bandwidth reallocation and optimal spectral utility on a near real time basis. SME offers reconfigurable, generic hardware that can be utilized to perform a complete set of essential functions independently through software control.

This paper describes the utilization of SME correlation capabilities to achieve three distinct classes of digital signal processing for communications and SIGINT applications: (1) cross-correlation matched filter, (2) autocorrelation spectrometer, and (3) time-delay synchronizer. Major features of these are shown in the figure below. The matched filter improves communication capacity and precision of emitter identification. The spectrometer permits dynamic spectrum management and the synchronizer allows tracking, direction finding, and nulling. Furthermore, the lower noise of the cryogenic superconductor receiver permits higher data rates, as well as detection of weaker transmit signals. By bringing the flexibility, fidelity and scalability of digital processing to the traditionally analog RF domain, this technology contributes to the objective of replacing custom analog systems with modular, general-purpose digital systems. While the above focuses on the receive side, similar capabilities can also be provided on the transmit side, to realize the full potential of the broadband, agile communication system.

1. INTRODUCTION

HYPRES is developing a broadband digital spectrometer for use with next-generation reconfigurable software-radio transceivers. Such a spectrometer will permit coarse spectral monitoring of the entire RF band, or fine monitoring (zooming in to MHz resolution or better) of any particular sub-band. This spectral monitoring will be critical in maintaining situational awareness, and is particularly valuable for the case of rapidly changing interferors, such as jamming signals associated with electronic warfare. Furthermore, together with high-level decision and control software, this spectrometer will enable true real-time ***spectrum management***, with dynamic band reallocation and optimal spectral utility. This is in contrast to current capabilities, which are generally limited to static band allocation in order to avoid potential spectral conflict and reduce possible RF interference.



The novel features of this digital spectrometer are enabled by broadband, high-fidelity digitization and ultrafast (20-40 Gbps) digital processing of RF waveforms, using superconductor rapid single flux quantum (RSFQ) technology. Two central elements of such a digital-RF receiver, the ADC and the digital correlator, have already been demonstrated by HYPRES in the laboratory. The low noise, high linearity, and high dynamic range of the superconductor ADC permits high-fidelity digitization of the entire RF band of interest, with detection of extremely weak signals as well as strong inteferors. As we show below, by correlating the input signal with itself (together with a programmable time delay), we can extract the RF spectrum quickly and efficiently. By bringing the flexibility, fidelity and scalability of digital processing to the traditionally analog RF domain, this technology contributes to the objective of replacing custom analog systems with modular, general-purpose digital systems.

There are two classic ways of obtaining the power spectral density function $S(\omega)$. The first, direct method, is to compute the Fourier transform $F(\omega)$ of the input $f(t)$ and multiply it with its complex conjugate to obtain

$$S(\omega) = F(\omega)F^*(\omega).$$

The second, indirect method, is to calculate the autocorrelation function $\boldsymbol{R(\tau)}$ from the input:

$$R(\tau) = \frac{1}{T}\int f(t)\, f(t-\tau)\, dt$$

where T is the integration period (much greater than the RF period) and τ is a delay time. It is well known that $S(\omega)$ is the Fourier transform of $R(\tau)$. The autocorrelation method is preferable for ultrafast (20-40 Gbps) digital-RF signals, produced by direct sampling of RF waveforms with a superconductor ADC, due to immensely simpler hardware realization. A single-bit oversampled autocorrelator has a simple and demonstrated RSFQ implementation: the digitized signal is progressively delayed through a clocked M-stage shift register, which corresponds to the time lag ($\tau = M/f_{clk}$), multiplication is done by a single exclusive-OR gate (XOR) and the integration is performed by an on-chip digital counter. The slow, multi-bit autocorrelator output could then be Fourier transformed using a room temperature processor to yield the power spectrum $S(\omega)$.

The block diagram of an autocorrelation spectrometer, with programmable span/resolution, is shown in Figure 1. The frequency span ($B = 1/\tau$) and resolution ($\Delta f = 1/M\tau$) can be programmed by choosing the autocorrelator time lag. The band of interest ($f_c \pm B/2$), which may be the entire receive band or any subband, is first digitally mixed down into separate upper and lower sidebands before performing the autocorrelation.

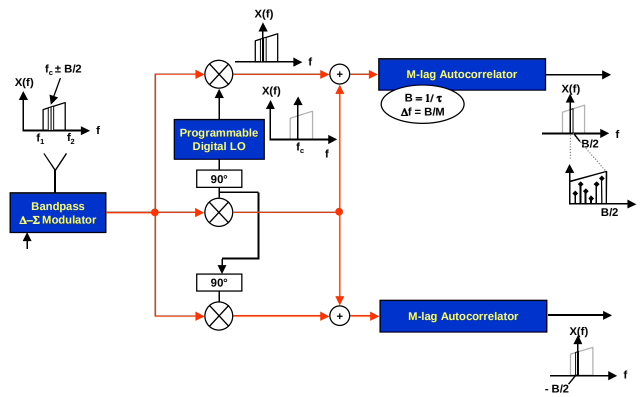


Figure 1. Autocorrelation spectrometer can choose a band of interest (of bandwidth B, centered around f_c) within the receive band and resolve its spectrum with a resolution of B/M. The bandwidth and the center frequency are programmable. This allows one to monitor a wide band and then selectively examine narrower sub-bands with proportionately higher resolution.

The digital flexibility of this spectrometer permits the user to zoom in to any particular region of the RF spectrum, and examine the spectrum in this region with greater precision. This involves tuning the digital local oscillator (LO) to any desired RF frequency, under full digital control. No special-purpose analog LO or analog mixer is needed as part of the hardware.

The HYPRES Spectrum Management Receiver strategy is (1) an Autocorrelation Spectrometer with programmable frequency span to monitor a wide RF band and zoom in on any narrower part of this spectrum with proportionately higher frequency resolution, followed by (2) Cross-correlation Matched Filters for reception of signals-of-interest by cross-correlation with RF waveform templates from a library, aided by the spectral information derived by the autocorrelation spectrometer. This provides ***Near Real Time performance unattainable with conventional technologies, capitalizing on the***

unique features of HYPRES Superconductor Microelectronics Technology. Figures 2 and 3 show some details of the approach.

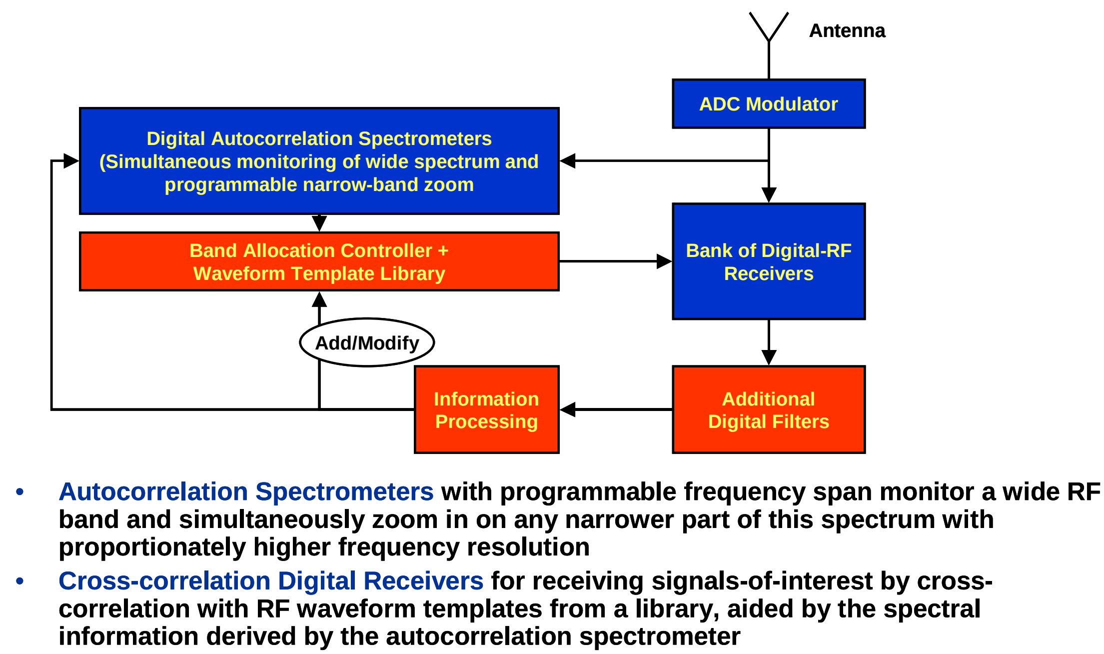


Figure 2. Digital-RF Spectrum Management

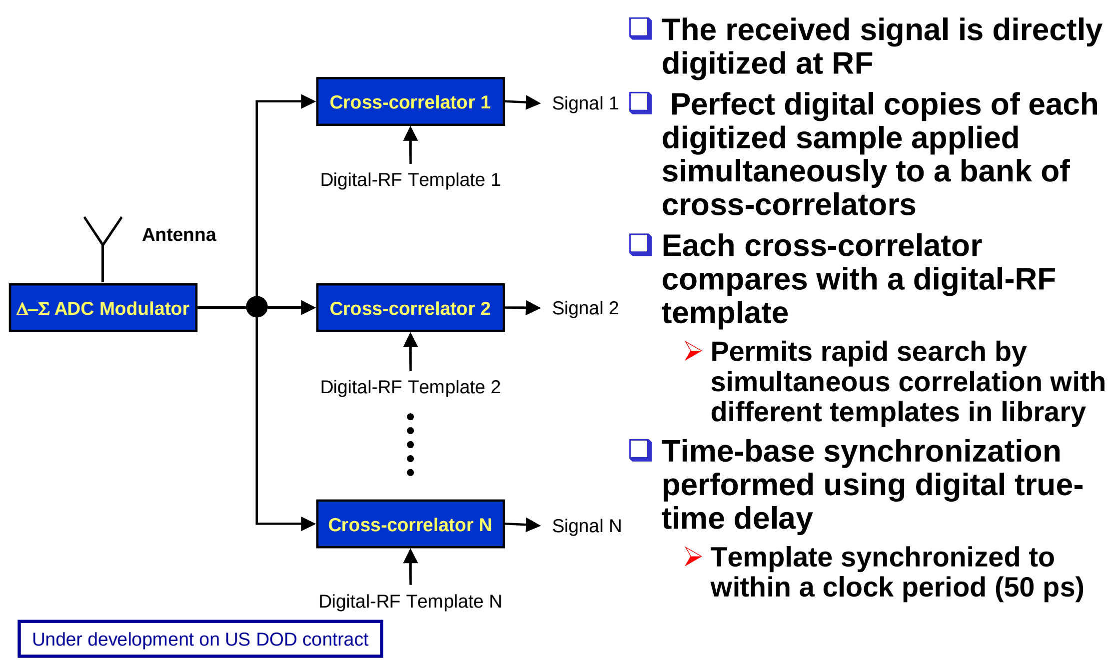
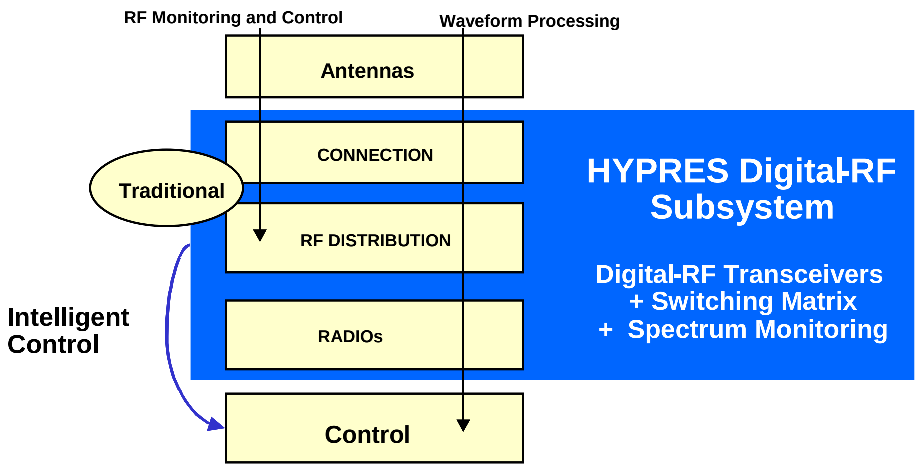


Figure 3. Digital-RF Cross-Correlator

The manifestation of these capabilities results in truly unique Spectrum Management. Figure 4 shows a Digital-RF Spectrum Management Architecture.

Only True Broadband RF Digitization supports both functions simultaneously



A digital-RF subsystem, integrating the waveform processing function with real-time detection of the RF environment through a reconfigurable RF switching matrix for efficient spectral management, is shown in relation with the traditional RF communication system architecture.

Figure 4. Digital-RF Spectrum Management Architecture

The unique benefits of SME technology as applied to Spectrum Management are shown in Figure 5.

- **Ultra-fast Correlation resulting in more rapid acquisition and superior processing -- over 1000X faster**
- **Rapid identification through digital-RF cross-correlation with library waveforms -- over 100X faster**
- **Reduction of minimum detectable signal by over 10 dB with low-noise ultra-sensitive front ends.**
- **Large near real-time (over 30 dB) correlation processing gain in signal-to-noise ratio for rapid ID, over 90 dB processing gain in 1 second**
- **Enhanced range of acquisition and signal processing**
- **Mitigation of Co-site interference virtually eliminating EMI problems**
- **Significantly improved direction-finding (>10x)**
- **Higher resolution, recognition, and dynamic range**
- **Ultra wideband capability**
- **Lower installation and life cycle cost**
- **Robust all-digital design provides "six-sigma" availability**
- **A universal platform, dynamically configurable for many platforms and services, that is scalable and expandable to add/reduce functionality for specific mission needs**

Figure 5. Unique Benefits for Spectrum Management

These unique benefits are derived from the following unique features of SME technology:

- **Ultra-High digital logic speed**
  Single Flux Quantum (SFQ) logic is the world's fastest (Devices ~10X faster than semiconductor, LSI ~ 50X faster than semiconductor)
- **Ultra-Low power dissipation**
  10,000X lower than semiconductor technology
  (Power dissipation for LSIC ~ 1 mW, Switching energy ~ 10^{-18} J)
- **Quantum accuracy**
  Defines the Volt
  (5ppb accuracy at 10V)
- **Fundamental linearity using magnetic flux quantization**
  Very High-SFDR ADC and DAC
  (Conversion between analog and digital domains through flux quantum (Φ_0 = h/2e) is independent of circuit parameters)
- **Extremely high sensitivity**
  SQUID (ADC front-ends) is the most sensitive energy detector
  ~60dB better than conventional semiconductor front end (Example: ~ -155dBm for 1 MHz BW, with slope of 20 dBm/decade)
- **Extremely low noise**
  Receiver System Noise Temperature $T_S \sim T_A$
  (Thermal noise at 4 K is 75X lower than room temperature)
- **Ideal interconnects**
  Speed-of-light transmission in LSI circuits, no RC delay
  Low-impedance superconductor interconnects have negligible loss, dispersion and crosstalk
- **Simple, inexpensive IC fabrication**
  Thin Film -- Much less expensive than semiconductors for fabrication facilities & equipment to produce chips
  (~10 steps, no expensive operations, orders of magnitude less)

Result: Digital-RF Technology

High-fidelity, wide band, high sensitivity digital representation and subsequent processing ("RF DSP": channelization, spectrum monitoring, true-time delay beamforming,..) of RF waveforms