Electronic Warfare Systems

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Invited Paper

***Abstract*—Electronic warfare (EW) is an important capability that can advance desired military, diplomatic, and economic objectives or, conversely, impede undesired ones. In a military application, EW provides the means to counter, in all battle phases, hostile actions that involve the electromagnetic (EM) spectrum—from the beginning when enemy forces are mobilized for an attack, through to the final engagement. EW exploits the EM environment by sensing and analyzing an adversary's application of the spectrum and imposing appropriate countermeasures (CMs) to hostile spectrum use. EW sensors are one means by which the military gathers tactical intelligence from noncooperative forces. EW sensors, together with EW CMs, mitigate the effectiveness of an adversary's electrooptic/infrared, and radio frequency-controlled weapons. EW enhances the survivability of the host force through control and manipulation of the EM environment and denies or limits its use by an adversary. EM spectrum CMs to threat systems can be selectively applied on a time- and/or frequency-multiplexed basis so that host force use of the EM spectrum is uninhibited.**

***Index Terms*—Circuit functions, complex modulation, cooperative sensors, counter countermeasures, countermeasures, digital receiver technology, electrooptic/infrared, electromagnetic environment, electromagnetic spectrum, electronic attack, electronic self-protection, electronic support, electronic surveillance, electronic warfare, filters, high-gain antenna, improved signal processing, independent sensors, isotropic antenna, offboard countermeasures, phased-array antennas, pulse code modulation, radar advancement, response techniques, sensor technology, spectral selectivity, subsystems sensors, threat systems, triangulation.**

I. Introduction

ELECTRONIC warfare (EW) is the systems approach to the exploitation and control, to the maximum extent possible, of the electromagnetic (EM) spectrum. It is an important capability that can advance desired military, diplomatic, and economic objectives or, conversely, impede undesired ones. The use by an adversary of the EM spectrum for communications, navigation, and radar functions can be challenged by the techniques and technology of EW systems. In a military application, EW provides the means to counter, in all battle phases, hostile actions that involve the EM spectrum—from the beginning when enemy forces are mobilized for an attack, through to the final engagement. EW exploits the EM environment by sensing and analyzing an adversary's application of the spectrum and imposing appropriate countermeasures (CMs) to hostile spectrum use.

Manuscript received April 6, 2001.

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Publisher Item Identifier S 0018-9480(02)01985-3.

A. Contribution to the Warfighter

EW sensors are one means by which the military gathers tactical intelligence from noncooperative forces. EW sensors, together with EW CMs, mitigate the effectiveness of an adversary's electrooptic/infrared (EO/IR), and radio frequency (RF)-controlled weapons. Land, sea, and air forces exploit the EM spectrum for command and control, weapons targeting, and weapons control. Fig. 1 shows multiple land, sea, and air platforms in a typical tactical environment. Also indicated are links for sensing, communications, and navigation in support of the military mission.

EW enhances the survivability of the host force through control and manipulation of the EM environment and denies or limits its use by an adversary. EM spectrum CMs to threat systems can be selectively applied on a time- and/or frequency-multiplexed basis so that host force use of the EM spectrum is uninhibited.

EW includes the operational functions of the following:

- electronic support (ES), which provides surveillance and warning information derived from intercepted EM environment emissions;
- electronic self-protection (EP), which protects the host platform against an electronically controlled threat;
- electronic attack (EA), which performs both ES and EP to protect a battle force composed of several platforms or battle units.

ES, EA, and EP functions are interrelated; EA and EP can be queued using ES information, and EA and EP can apply some of the same sensing and CM equipment for distinct operational objectives.

This article describes the signal environment in which EW systems operate and the subfunctions and technology required to conduct EW. A discussion of EW functional areas (ES, EP, and EA) provides a framework for supporting EW technologies.

B. Historical Background

The development of radio technology in the 20th Century and its extensive application to communications, radar, and navigation provided the military with powerful tools. Radio communications were developed to coordinate forces; radio navigation provided accurate location of the deployed forces; and radar performed surveillance of the battle space to verify force deployments and detect hostile forces. This technological environment, together with the attendant military and political threat, gave impetus to the development of EW technology to offset the advantage provided by hostile RF technology.

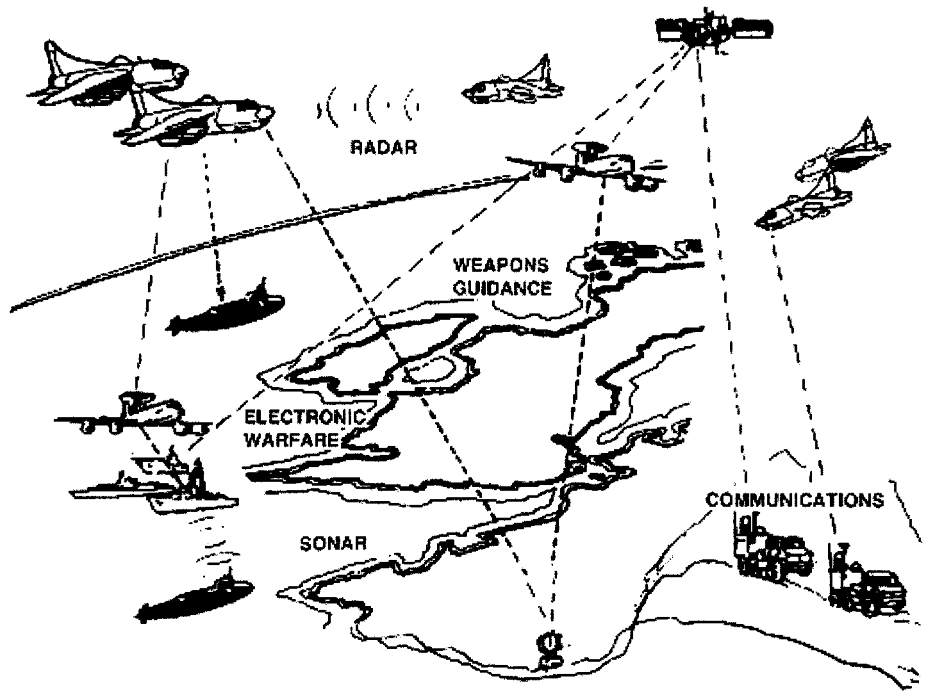

Fig. 1. EW tactical environment.

A review of the radar and infrared (IR)-guided surface-to-air missiles (SAMs) and radar-guided antiaircraft guns from World War II (on display at the U.S. Army Ordnance Museum, Aberdeen, MD, where historic military ordnance are restored and preserved) indicates the sophistication of the EM-spectrum-based threat systems of more than one-half century ago. Initially, EW used the technology of the threat systems—superheterodyne receivers, klystron and magnetron signal sources, and vacuum tube amplifiers and oscillators. Subsequently, broad-band channelized and pulse compression receivers and traveling wave tube (TWT) and crossed-field amplifiers were developed that addressed EW system needs.

Early military use of radio transmission for directing ordnance and troop deployments was rapidly countered by adversarial exploitation of these same transmissions. A message rapidly comprehended by an unintended interceptor could be as valuable to the exploiting forces as to the intended recipient. Even without message comprehension, the location of the transmission could be determined by radio triangulation, and the functional origin of the message could be inferred from other intelligence sources. This provided valuable military information to the force exploiting EW technology.

These same techniques were later applied to the exploitation of radar signals. Classical pulse code modulation (PCM) radar is a time-based process to determine and refine target location. The PCM structure provides an indication of the radar function that, together with the radar location, provides valuable information for CM or operational alternatives that decrease the effectiveness of the adversary's radar-controlled weapon system.

EW microwave technology evolved from the critical need to rapidly extract essential information from the EM environment. This information is then exploited to influence an adversary's perception of the surroundings by controlling the signature of cooperative ships and aircraft and injecting microwave energy into the environment, thereby creating a deceptive representation. EW sensor technology advanced from initial superheterodyne and crystal video receivers to wide-band channelized acquisition receivers coupled to precision analysis receivers. In addition, EW signal processors evolved from operator analysis of filtered audio signal detection to digital signal-processing analysis of complex signal environments. These advances provide rapid environment analysis and threat signal classification and characterization. EW CM developed from convection-deployed screening chaff and narrow-band vacuum tube noise jammers to remotely piloted vehicles carrying seductive CMs and coherent deceptive countertargeting jammers.

The earliest attempts to develop IR passively guided weapons homing on the positive contrast of heat-generating target structures occurred in World War II. Nazi secret-weapons projects included two IR-guided antiship missiles, i.e., a flying torpedo and a glide bomb, the Hailstone. Both were to be terminal phase sea skimmers, with a terminal altitude of 3 m. The first attempted IR-guided SAM Wasserfall was also a Nazi secret-weapons project. This weapon was developed as a derivative of the V-2 rocket; it was designed to have IR homing and self-contained guidance. Fortunately, none of these weapon systems were completed.

II. EW System Drivers

A. Environment

The EW system shares the physical and EM environment with communications, radar, and navigation systems. The environment presents both impediments and opportunities for effecting the EW objectives of providing own-force systems use of the EM spectrum while reducing the effectiveness of an adversary's systems. Terrain contours can obstruct the signal transmission

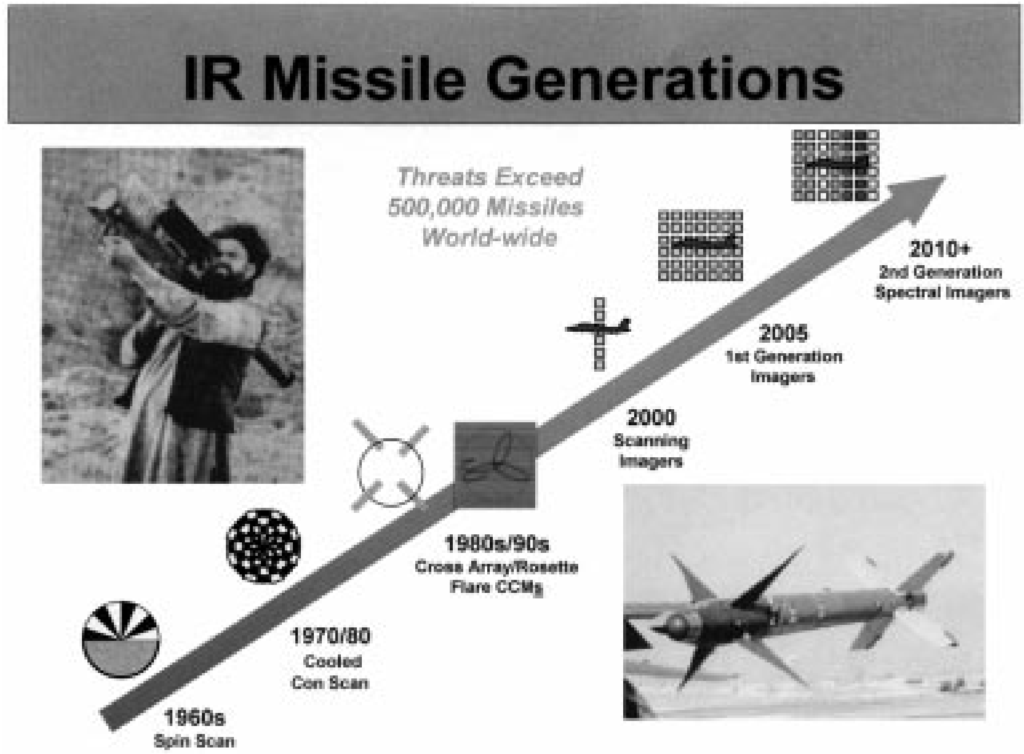

Fig. 2. EO/IR weapon sensor time line (courtesy of W. R. Taylor, Air Force Research Laboratory).

path necessary for signal exploitation. Conversely, a propagation duct can enhance the received signal level and enable signal detection and exploitation far beyond nominal range. Likewise, intercepted threat signal energy provides the EW information necessary to characterize the tactical environment, but interfering signals can preclude detection of target emitters.

B. Threat Systems

EW interacts with an adversary's EM systems for signal exploitation and, potentially, for EA. Threat systems of EW interest include radar and communications. Some of the threat systems exploited by EW are briefly described in the following.

1) Radar: Radar with RF transmissions ranging from high-frequency (HF) to millimeter (30 MHz–95 GHz) waves, in pulsed and continuous-wave (CW) modes, illuminates targets and collects reflected echoes [1]. Radar-transmission-reflected echoes are used to measure target characteristics and determine target location. Military forces use radar for both offensive and defensive weapon systems. Radar functions include target detection and identification, target acquisition, target tracking, and navigation. Radar weapons systems may be land-based, airborne, shipboard, or in space. A typical radar system contains a transmitter that produces a high-powered RF signal that is tunable over a band of frequencies; an antenna system that radiates energy and collects reflected echoes; a receiver that detects signal return; and signal processing electronics that extract target measurements such as range, bearing, and speed. Target location information is provided to a weapon system to control and direct the weapon onto the target.

Radar advancements can be expected in the areas of phased-array antennas, complex modulations on the radar pulse, improved signal processing to extract enhanced data from the radar return, and frequency diversity to cover the less used regions of the spectrum. Operational needs for enhanced sensor performance will drive the development of advanced designs by both friend and foe because of the availability of affordable technologies to provide additional capability.

2) Communications: HF direct microwave and satellite relay command and control communication links disseminate voice and digital data transmissions to land forces, air forces, and ships [2], [3]. Land combat units use ultrahigh frequency (UHF) (300 MHz–3 GHz), very high frequency (VHF) (30–300 MHz), landlines, and cellular phones over shorter distances mainly for voice transmissions. Surveillance activities and weapons sites may exchange data via voice or digital data link over a transmission path appropriate for the link span. Such links transmit surveillance radar reports to an operations center or directly to a SAM battery. Communication link data rates depend on link bandwidth, modulation technique, and signal-to-noise ratio. Individual transmission-link throughput rates are in the range of hundreds of megabytes per second. Computer technology has enabled increased communication-link capacity for handling and processing data. The high data rates attainable permit transmission from airborne observers and between precision weapons and launch platforms.

3) Infrared/Electrooptic (IR/EO) Threats: Since the Vietnam era, there has been a steady growth in both the sophistication and variety of IR/EO-guided weapons [4], [5]. The diagonal line of Fig. 2 traces the evolution of IR seeker spatial processing from the spin scan reticle to the focal plane. The absolute numbers, as well as the varieties of IR/EO-guided air-to-air, surface-to-air, air-to-surface, and surface-to-surface

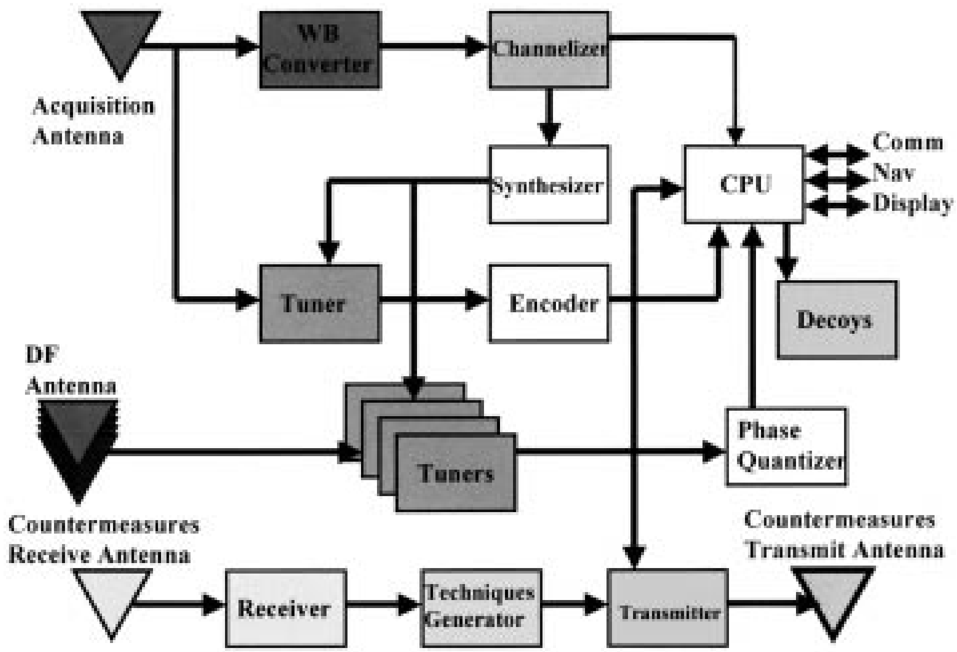

Fig. 3. EW system architecture.

weapons is projected to continue to grow. The growth of multirole guidance weapons designed to attack targets on land, sea, or in air is also increasing. Another growth trend is in the development of hybrid IR/EO-RF guidance. These hybrids provide a high-resolution three-dimensional target space that greatly complicates the EW response. Operational examples of the variety of IR/EO guided threats are indicated in the pictorial inserts of Fig. 2, which show a guerrilla soldier with a handheld SAM and a surface-to-surface missile mounted to a fighter aircraft pylon.

III. EW System Architectures

The EW system architecture ties system functional elements into an efficient configuration optimized to an operational mission. In the evolution of current and projected EW implementation, EW system architecture is an expanding concept. This discussion will progress from the current definition of system architecture, which encompasses EW assets aboard a single platform, to the broader definition that includes other systems onboard and, subsequently, to any available battle group EW asset and to all available tactical and strategic EW assets.

Fig. 3 shows a typical onboard EW system architecture. The system performs signal acquisition and parameter measurement, direction finding, CM generation, and decoy deployment. The system central processing unit (CPU) provides sensor and CM coordination and EW system interface with other onboard systems.

Fusing the measurements of EW sensors and processors with those of other platform functions is a complex technological challenge. Collateral information includes radar, communications, EO/IR, direction finding, and signal analysis. Data fusion within the EW system requires algorithmic development and significant enhancement in computational throughput. The EW system includes antenna(s), receiver(s), and processor elements that provide data on signals in the environment. System sensors detect and measure threat signal characteristics. Multiple sensor subsystems measure the characteristics of the signal. For example, a signal acquisition sensor detects the presence of a signal and measures the envelope characteristics (frequency, time of arrival, and signal duration). Another sensor, which may include multiple antennas and receivers, provides signal bearing-angle data. Separate subsystem sensors measure intrapulse signal modulation and/or received polarization.

A CM receiver may have an independent EM environment interface. The CMs receiver accepts signals from the environment and provides them to the techniques generator. Target signals designated by CPU algorithms are selected for CM generation, as are the CM modulation techniques to be applied. The resulting jamming signals are amplified to the desired power levels and radiated into the environment.

Decoys are part of the EW system architecture. This subsystem is controlled by the CPU based on sensor inputs. Decoys provide the important function of separating the CM signal source from the host platform. In this operational mode, decoys provide alternative highly visible targets to divert a weapon from its target. Also required are the means, such as the coordination of jamming with the deployment of decoys, to neutralize the home-on-jam (HOJ) weapons threat.

A. Cooperative and Independent Sensors

ES sensors to provide critical battle space information to warfighting units, ships, aircraft, and land battle formations. Conventional deployment of ES sensing is in support of the host platform. Environmental information provided through these sensors is timely since only the signal propagation and processing latency produce warning delay. However, signal source spatial information is not instantly generated, and the convergence of a location solution can occur much more rapidly when multiple platforms exploit the transmitting signal.

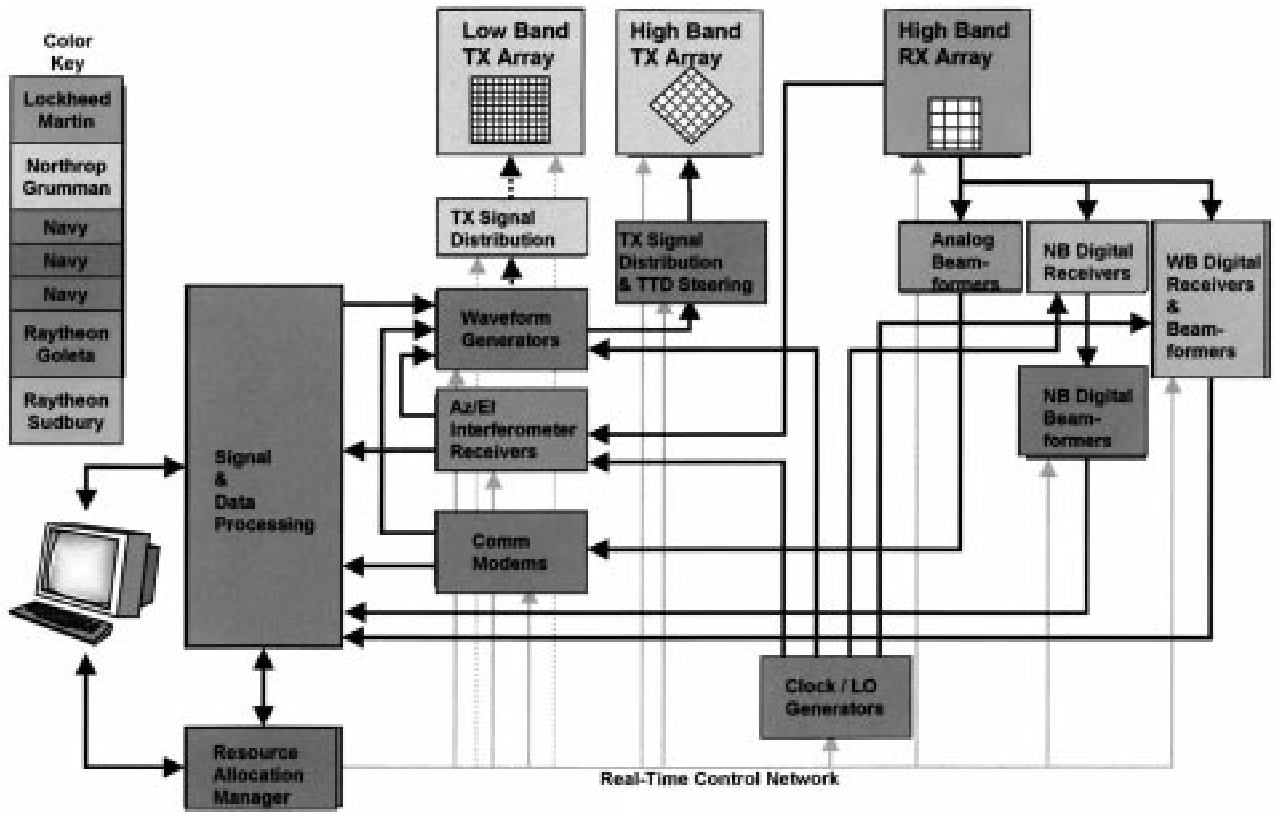

Fig. 4. Multifunction equipment supporting EW.

In addition, a network of sensors can enhance warning by providing over-the-horizon threat signal detection.

Currently, processed signal intercept information is shared among platforms through a communications network. This information provides platforms within the battle space with an image of the operational situation as seen from many sensor locations. The processed information currently shared provides valuable tactical information, but it is assembled from only a fragment of the data available to all battle space ES sensors. With signal classification and geolocation determined from independently measured data fragments, the probability for correct signal classification is reduced and the location ellipse diameter is increased. Consequently, ES sensor networking efforts seek to mutually provide measured ES data from all battle space platforms so that more accurate signal classification, identification, and physical location can be determined quickly.

B. Multifunctional Systems

Research initiatives in EW address sharing of assets, microwaves, signal processing, and user interface with other platform functions. In this way, the high-value antenna, microwave processing, and digital signal processing do not have to be replicated for each microwave function onboard. Efficiencies result from multiple-use equipment and also from the ability to share data across system functions.

Fig. 4 depicts the integration of EW functions with other platform functions. Of particular interest is the sharing of high-value antenna and microwave resources. System element consolidation can provide superior assets to all of the functions serviced. Research supporting this concept is currently underway in the Advanced Multifunction Radio Frequency Concept (AMRFC) demonstration sponsored by the U.S. Office of Naval Research. In this project, common phased-array antennas simultaneously service EW, radar, and communications functions. Common equipment includes broad-band phased-array microwave apertures, microwave processing, signal and data processing, and integrated function control and display.

C. Interplatform EW Functional Integration

Advances in communication technology are providing an infrastructure that can link multiple platforms and integrate EW sensor information. The network centric approach to EW, shown in Fig. 5, has the potential for enhanced system response time and increased accuracy. The network centric concept envisions multiple EW systems spatially distributed in the environment providing assets to the overall EW functional objective. Sensors located on various platforms measure environment signals from different perspectives. Signal ambiguities can be more rapidly resolved with data from platforms physically isolated from sources of ambiguity. Correspondingly, the location of resolved emitters can occur more rapidly since combinations of sensors with orthogonal perspectives of the threat emitter resolve emitter location more rapidly.

Coordinated multiplatform CMs, either for counter-targeting or self-protection, provide enhanced capability. Spatial diversity of either active or passive CM can create virtual environments that greatly dilute the real environment and impact an ad-

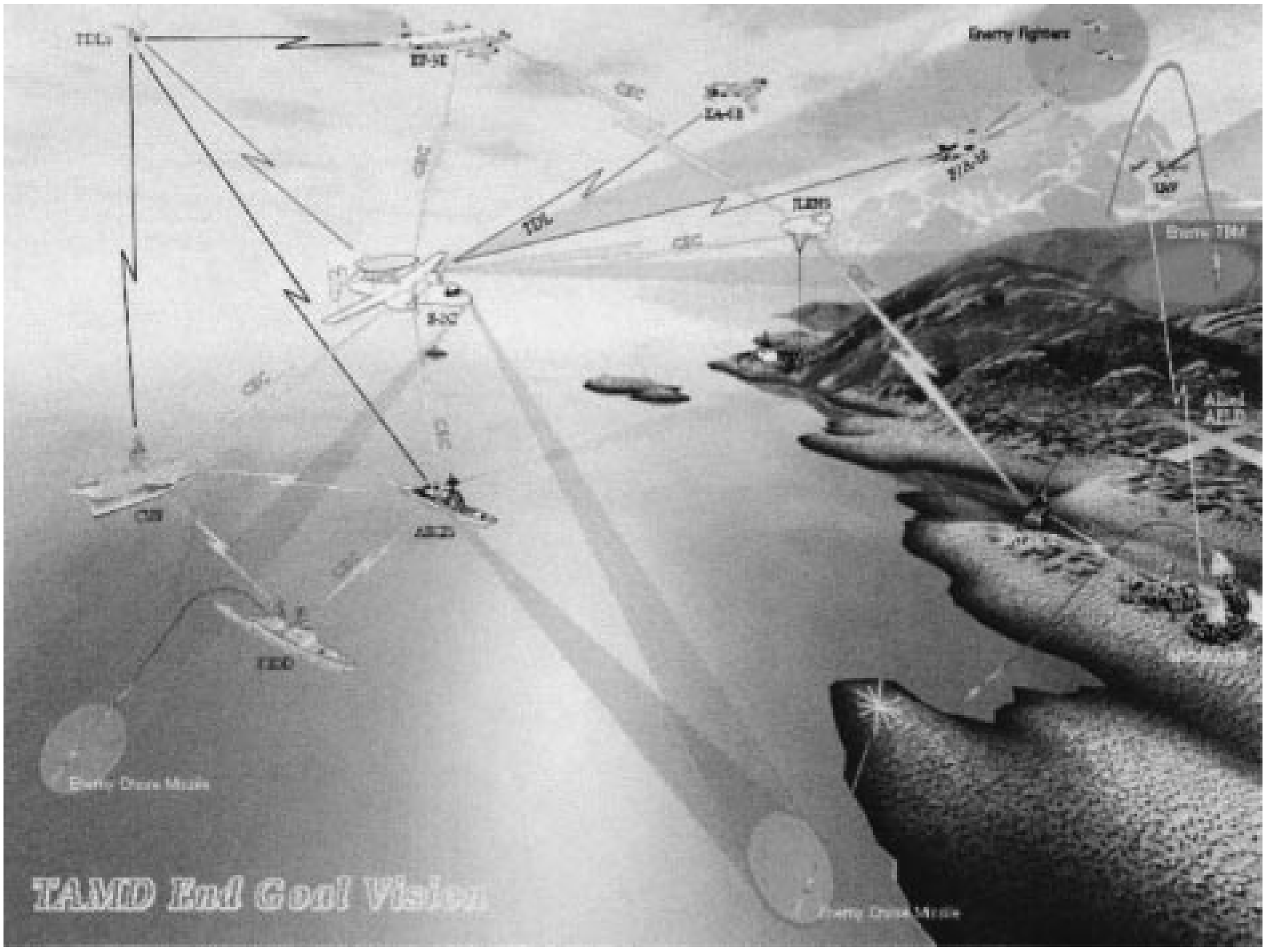

Fig. 5. Network centric EW concept.

versary's operational decisions. The perceived deployment and environment density projected by CM through an adversary's surveillance radar could delay that adversary's operational decision or provoke less than optimal maneuver. The enhanced CM effectiveness from distributed EA results from the dilution of true environment targets with virtual electronic-CM-generated targets and the resulting reduced probability that the weapon will engage a real target.

IV. EW Technology

A. ES—EW System Sensor

ES provides surveillance and warning information to the EW system. ES is a passive nonradiating EW system function that provides a fast accurate assessment of the EM radiating environment. ES is the aspect of EW that involves techniques to search for, intercept, locate, record, and analyze radiated energy. ES provides EW information for use in EA and EP and in tactical planning. ES directly provides threat identification/detection and early warning. It also provides data for EP, threat avoidance, target acquisition, and homing.

ES provides timely EM environment information for the EW system. The spatial and spectral environment over which ES operates may span a hemispherical spatial segment and a spectrum of tens of gigahertz. In tactical EW systems, signals in the environment are analyzed and reports of environment activity are provided on the order of a second after threat signal reception.

A frequently updated survey of environment spatial and spectral signal space provides timely surveillance and warning. System design must consider feature tradeoffs. These include instantaneous spatial coverage, spatial segmentation, instantaneous spectral coverage, spectral segmentation, and the computational power necessary to segment spatial and spectral coverage and process measured data. Different approaches are used for warning and self-protection ES versus surveillance. Aircraft, land-based, and shipboard ES implementations also show differences in approach.

EW signal intercept and analysis is characterized by contending requirements for wide instantaneous operating bandwidth. This provides rapid signal environment intercept and the large dynamic range necessary to detect threat signals at great distances in the presence of local background and own-force transmissions. The requirement for wide instantaneous bandwidth in a high dynamic-range signal environment demands the use of high dynamic-range wide-band receiver elements and spectral selectivity, where applicable, to reduce interference from emissions near the EW system. To accommodate the wide range of signal levels encountered in tactical environments, higher power wide-band processing elements, amplifiers, limiters, and mixers are used. RF notched filters can be integrated into a wide-band receiver RF processor to reduce interfering signal levels before they arrive at nonlinear RF processing components.

Monolithic microwave integrated circuit (MMIC) technology provides wide-band high dynamic range to EW receivers. MMIC implementations of feed-forward power summation and interference-cancellation amplifiers increase the dynamic range of these components. High bandgap mixer switching elements provide wider dynamic-range frequency converters. Fixed tuned notch microwave filters can selectively reduce signals to attenuate interfering emissions. Yttrium–iron–garnet (YIG) filters attenuate higher level interfering signals from sources with variable operating frequency.

A broad range of microwave and optical technologies address the RF signal processing needs of EW systems. These technologies promise the performance enhancements required for optimum ES system operation in emerging threat environments. Analog fiber-optic technology is being developed to efficiently transport microwave signals between ES system elements. Microwave optical processing development addresses the multiplexing and demultiplexing of microwave signal channels for coherent processing of the microwave environment. Magnetostatic wave (MSW) technology promises to provide highly resolved spectral processing within a wide-band transmission medium. High bandgap semiconductors, such as silicon carbide, are being developed that can operate at the higher power levels necessary for high dynamic-range amplifier and converter elements. Monolithic electromechanical semiconductor (MEMS) technology that addresses both ES sensitivity and dynamic range issues is being applied to low-loss microwave switching preselection.

B. EW Engagement

To engage an approaching threat, the EW system has a toolkit of response techniques. The choice of proper response is predicated on correctly identifying the receive portion of the EW system of the threat. Typically, the response portion of the EW system has at its disposal onboard and offboard techniques. The techniques are executed along a time line in what is referred to as a "tactic." Several techniques may be combined into one tactic.

Although all variants of the shipboard-deployed CM system (AN/SLQ-32) (Fig. 6) can engage threats, some are capable of engaging threats with an active onboard countermeasure (AECM) group. The AECM group includes all hardware resources necessary for transmitting confusion and/or deception jamming signals. The system uses a Rotman lens, which evenly divides the signal environment applied to its input among its 35 output ports that correspond to spatial segments. Signals at each output port are of slightly different phase to produce one beam aimed in the direction of the threat. Prior to being emitted from the antenna, the signals are amplified by TWT-type amplifiers.

The AN/SLQ-32 has several shortcomings. These include limited elevation coverage, limited number of threats that can be engaged with onboard active EA, limited polarization diversity, high sidelobe levels, high radar cross section (RCS) levels, and transmitter-to-receiver isolation issues.

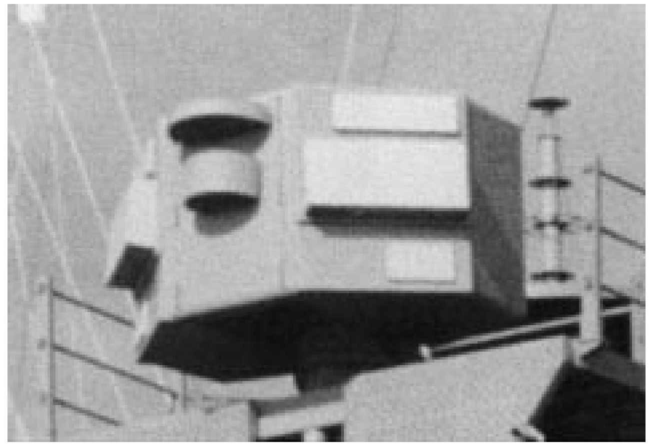

Fig. 6. Shipboard EW antenna assembly (AN/SLQ-32).

C. Offboard CMs

A variety of decoys complete the toolkit of engagement responses. Effective EA from small affordable decoys is a long-standing objective of EW. The goal is to generate large radar cross-sectional targets, with appropriate signatures to defeat the evolving air and surface missile threats. The need for improved offboard, i.e., decoy, systems became more acute as threat systems evolved to incorporate counters to the onboard EA systems. Threat system CCM onboard EA systems include weapons monopulse tracking.

Passive offboard EA systems, primarily chaff, are limited by advances in doppler processing and other chaff-discriminating techniques found in improved antiship cruise missiles (ASCMs). These passive decoy systems were also operationally encumbered by the operating environment, e.g., the wind, in the case of surface combatant protection.

The key to developing and fielding offboard microwave decoy systems has been the significant improvements made in microwave and microwave-related components. Pivotal microwave technology developments include modest power, affordable, low-noise-figure solid-state microwave amplifiers; the practicality of MMICs; large bandwidth, high-power high-gain TWTs; and improvements in small efficient broad-band antennas.

TWT technology advances have been paralleled by advances in microwave antennas and MMIC devices such as filters, mixers, switches, and limiters. These advanced components can readily be combined into a form factor usable as a decoy.

The future of microwave technology for EW decoy applications points to increased bandwidth, with capabilities expanding into the millimeter-wave (MMW) spectrum (20–100 GHz). EW decoy applications require MMW technologies with performance comparable to that achievable at microwave frequencies. Single-component coverage of the entire microwave and MMW band is even more desirable.

Extended application of solid-state amplifiers in nonplanar arrays and the networking microwave components to drive these amplifiers is essential in decoy technology development. Vacuum tube device capabilities must also be enhanced to provide decoy single-component microwave sources that operate from modest current high-voltage sources [6].

A more rigorous integration of optical technologies with microwave technologies is essential and is currently underway to bring further enhancements into current designs. Future integration of these technologies will provide additional improvements and, based on ongoing laboratory testing, will significantly increase on our current capabilities to address the threats.

As our microwave technologies improve, it is essential that we protect our most critical breakthroughs. This has become increasingly difficult in the current nonmilitary cost-conscious commercial environment. However, military weapon threat systems also take advantage of the same improved microwave technologies to improve their performance at a rate comparable to or exceeding the rate with which we counter their evolving capabilities.

V. Key EW Microwave Technologies

A. Antennas

1) Isotropic Antenna: Airborne and land-based warning and self-protection ES typically uses isotropic antenna elements to provide a wide instantaneous field of view. These antenna elements can be anechoic loaded Archimedean or linear cavity-backed spiral antennas. They provide a wide instantaneous field of view over a wide bandwidth. The low-frequency cutoff of the antenna is established as the frequency at which the antenna diameter measures one half-wavelength. The high-frequency antenna cutoff results at a frequency where connections to the spiral arms span a significant fraction of a half-wavelength. Spiral antennas can be configured to provide either right-hand- or left-hand-side circularly polarized signal intercept. These antenna elements can be configured into an angle measurement array by using either amplitude or phase differences between elements to establish the incident angle measurement.

2) High-Gain Antenna: Operational ES surveillance systems use antenna gain to provide backlobe detection and characterization of environment signals. High-gain antennas can be queued from a receiving system by using a lower gain isotropic antenna or, alternatively, they can survey the environment by scanning over a selected spatial sector. The conventional high-gain antenna is either a slotted horn antenna or an antenna that uses a reflector. Note that along with increased sensitivity, greater antenna gain also prolongs the environment scan because the antenna instantaneous field of view is inversely proportional to antenna gain $\theta^2 \propto K/G$, where θ is the single-dimensional angle field of view, G is the aperture gain, and K is a constant. In addition, increased antenna gain can result in the reception and detection of extraneous multipath signals in the environment that reduces probability of intercepting the true threat signals and increases the signal-processing difficulty.

B. MMIC Receiver Technology

ES MMIC hybrid modules include circuit and subsystem design networks that use cancellation techniques to achieve small size and low power dissipation with high dynamic range. Common configuration microwave front-end hardware provides the affordability necessary for EW and ES systems.

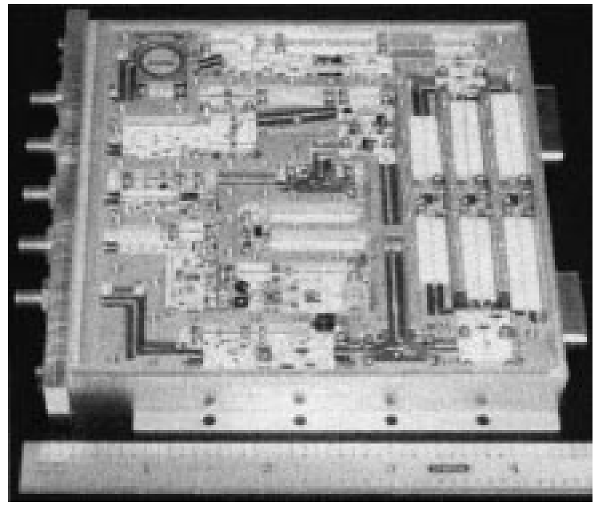

Fig. 7. Wide-band MMIC receiver assembly.

1) Modular Wide-Band Converter: A group of MMIC receiver modules conform to a standardized outline, mounting, and interface that can be integrated into VERSA module Eurocard (VME), VME extensions for instrumentation (VXI), and standard electronic module-size E (SEM-E) configurations, as well as standalone custom configurations. Fig. 7 is an example of such a module. This module is a wide instantaneous bandwidth frequency converter with input frequency coverage of 0.4–18 GHz. Intermediate frequency (IF) output options include 3–5 GHz, 2–4 GHz, and 2–6 GHz.

This converter uses image rejection as implemented with coupled line filters in the 6–18-GHz input in lieu of the heterodyne spectral image reject mixer. The high-band mixer is an open-carrier-based double-balanced mixer using packaged diodes.

C. MMIC Transponder Technology

Fig. 8 shows a portable standalone battery-powered transponder that modulates received signals, amplifies the modulated signal to 2 W, and retransmits the signals. The combination of choke rings on the outer body of the decoy, antenna design, and internal packaging and associated circuitry provide 100 dB of isolation from output to input, which prevents system oscillations.

A single-sideband modulator was developed using a pair of gallium–arsenide (GaAs) semiconductor MMIC in-phase and quadrature (I/Q) signal phase mixers in a cancellation network. The cancellation network includes an in-phase splitter at the input and a 180° hybrid at the output. This technique cancels the incoming RF and passes the modulated signal at the output for sideband and input signal rejection. The unit is in a low-power mode until a signal is detected, at which time the unit changes status to a full-power transmit mode. To minimize battery drain and for high efficiency, p-doped semiconductor high electron-mobility transistor (pHEMT) hybrid tuned amplifiers have been developed.

Major circuit functions include transmit and receive antennas, a detector logarithmic video amplifier (DLVA), automatic level

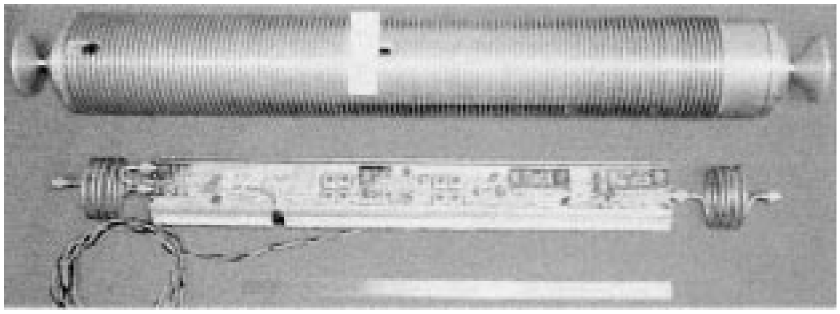

Fig. 8. Microwave transponder assembly.

control (ALC), 100 dB of X-band (8.0–12.0-GHz frequency range) gain, a single-sideband modulator, a techniques generator, a battery-operated power supply, and 2-W output power.

D. IF Microwave Processor

The ES IF microwave processor accepts the IF output of the MMIC converter(s), processes the applied environment segment, and measures and characterizes signals therein. In this process, environment signals are digitally encoded into descriptors for subsequent digital signal processing. The receiver architectures are quite varied, and some are discussed briefly. Early ES systems were single-channel and narrow-band. All signal data are characterized at the output of the narrow-band receiver channel, and the directional antenna shaft encoder measures signal bearing.

As threat signals appeared across broad ranges of the microwave spectrum, the ES system required sensors capable of observing the environment across a broad, spatial, instantaneous field of view, and frequency range. These sensors were needed to realize an acceptable time for environment signal intercept. Broad-band parallel ES architectures evolved that combined signal event parameter measurements from the onboard sensors. As the density of the signal environments increased, interference between signals in the broad spectral and spatial operating environment and the temporal proximity of signal event reports made the correlation of ES sensor descriptors and the generation of accurate composite event descriptors difficult.

A queued ES architecture evolved to reduce interference. The queued architecture provides broad-band signal acquisition and narrow-band signal measurement. A channelized wide-band receiver servicing the acquisition sensor reduced the effects of interfering signals and provided a coarse frequency signal event measurement. The signal measurement receiver, set on frequency by the acquisition receiver, accepts a delayed wide-band environment, selects the segment of the spectrum indicated by the acquisition frequency measurement, and measures and digitizes the signal event characteristics. Cued precision measurement assets are time-division multiplexed to sequentially measure signal events. The ES cued architecture provides selectivity in the measurement channel to reduce the effects of interfering signals. It also provides precise measurements for signal characterization.

Modern radar signal modulations are characterized by higher duty cycle transmissions that create time-coincident pulses at the ES system. Multiple copulse signal events require either multiple measurement assets or signal processing capable of characterizing the environment. Since processing requirements grow significantly as pulses in a train are deleted, the addition of measurement assets is desirable. The preferred ES receiver architecture is evolving from the cued architecture to precision parameter measurement in all channels of a channelized receiver. The range of microwave technologies studied for ES channelization include microwave filter demultiplexers, stripline-coupled resonators, coupled dielectric resonators, stripline filter banks, and coupled MSW filters, as well as surface acoustic-wave and bulk acoustic-wave demultiplexers, acoustooptic channelizers, and digital channelized receivers.

E. Microwave Filter Technologies

Microwave filter technology has been steadily evolving over the last 20 years [7]. It has been driven by the extreme performance requirements of military radar and EW systems, the low-cost demands of commercial data links, and recently the subminiature size constraints of mobile personal communications. Microwave filters and multiplexers separate, combine, or shape signals in the frequency domain, although often their time-domain response may also be important. The following is a review of the various technologies being used to realize microwave filters, their important characteristics, and typical applications.

1) Microwave Filter Implementation Technologies: Applications where filter insertion loss is not the prime consideration can benefit from printed circuit techniques that combine low-cost and high-volume manufacture with excellent reproducibility and performance tracking. Where physical size is important, the use of high dielectric-constant substrates (such as alumina) significantly reduces size. Microwave filter implementation approaches include stripline, microstrip, E-plane, and dielectric-resonator filters. Recent developments in MMICs have led to the ultimate size reductions, typically down to a few square millimeters and can include active field-effect transistor (FET) devices.

2) Controllable Filter Technologies: The switched filter consists of a bank of bandpass filters and multiway switches, arranged so that any combination of filters can be simultaneously selected. Typically, the filters are machined or printed combline designs and the switches are p-i-n (positively doped semiconductor, intrinsic semiconductor, negatively doped semiconductor) diodes or, for lower frequencies, FETs. Fig. 9

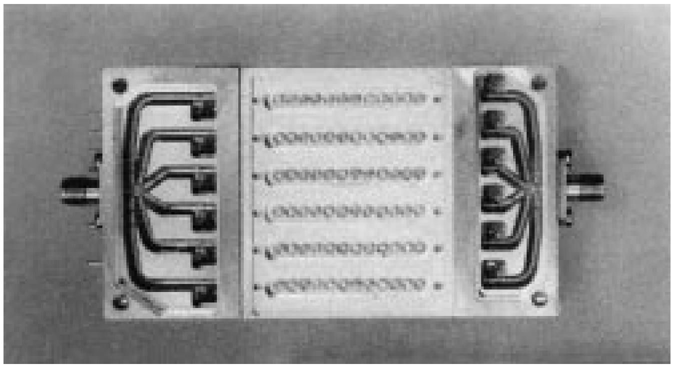

Fig. 9. Microwave switched filter assembly.

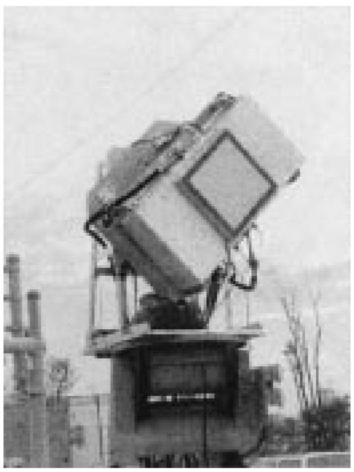

Fig. 10. EA phased-array antenna assembly.

shows a machined combline six-channel switched filterbank with p-i-n switches at K band (20.0–40.0 GHz).

VI. The Future

Future EW microwave technologies will include extensive use of phased-array technology, nonlinear magnetic microwave devices, optical microwave signal processing, and microwave digital receivers. These technologies will emerge to functional prominence in EW systems, even as existing technologies evolve to answer the increased system performance needs. Continued development in TWT and solid-state amplifiers, discrete and monolithic filters, antenna elements, and apertures, as well as microwave demultiplexers and broad-band memory, can be expected as needs for improved performance drive the development in existing technologies.

A. Phased-Array EA

Phased-array technology is being developed to address the shortfalls in EA shipboard self-protection [8]. To this end, a high-power broad-band active (GaAs power modules) aperture array for the EA application was developed (Fig. 10). This implementation featured photonic true-time-delay beam steering. It also performed risk reduction and environment demonstrations to enhance confidence in this technology for the next-generation shipboard EW system.

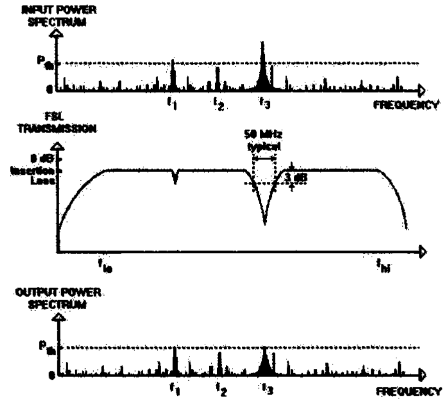

Fig. 11. Magnetostatic selective limiter performance function.

An ambitious development is being pursued that combines shipboard surveillance, communications, and engagement functions into a single aperture. This project, i.e., AMRFC, manages RF shipboard emissions and makes efficient use of platform aperture space. A significant challenge for transmitter phased-array applications is the development of new "wide-bandgap" microwave semiconductor materials capable of greater operating temperatures, specifically gallium–nitride (GaN) and silicon–carbide (SiC). Another major phased-array technology challenge is the EM isolation required for multiple systems using the same aperture.

B. Nonlinear Magnetic Microwave Devices

1) Frequency-Selective Limiter (FSL): EW systems are required to work in high signal density environments that include high-power interfering signals. Under these conditions, conventional receivers can generate intermodulation responses that easily overload the EW signal processors. Also, receiver saturation can cause desensitization that precludes weaker signal detection. A diode-limited wide-band receiver attenuates all signals and generates intermodulation responses. An FSL [9] attenuates strong signals without attenuating other time-coincident weaker signals (Fig. 11).

Microwave FSLs use the frequency-selective nature of a magnetized ferrite. At low-signal levels, the coupling to modes is negligible and the signal is propagated with little attenuation. Above some critical RF magnetic-field level, the precession angle can increase no further, and coupling to higher order spin waves, begins to grow exponentially. Energy is efficiently coupled to spin waves at approximately one-half the signal frequency. Some of the RF energy is coupled from these half-frequency spin waves into lattice vibrations in the ferrite, causing the excess signal energy to be dissipated as heat.

2) Signal-to-Noise Enhancer (SNE): Another related nonlinear device is the SNE. It performs the opposite function to the FSL. At low signal levels, the SNE absorbs most of the signal energy. At high signal levels, the absorption mechanism saturates, allowing a larger fraction of the signal to pass. As in the FSL, this effect is frequency selective, meaning that the SNE can attenuate low-level signals such as broad-band noise, while allowing strong coherent signals to pass with relatively little attenuation.

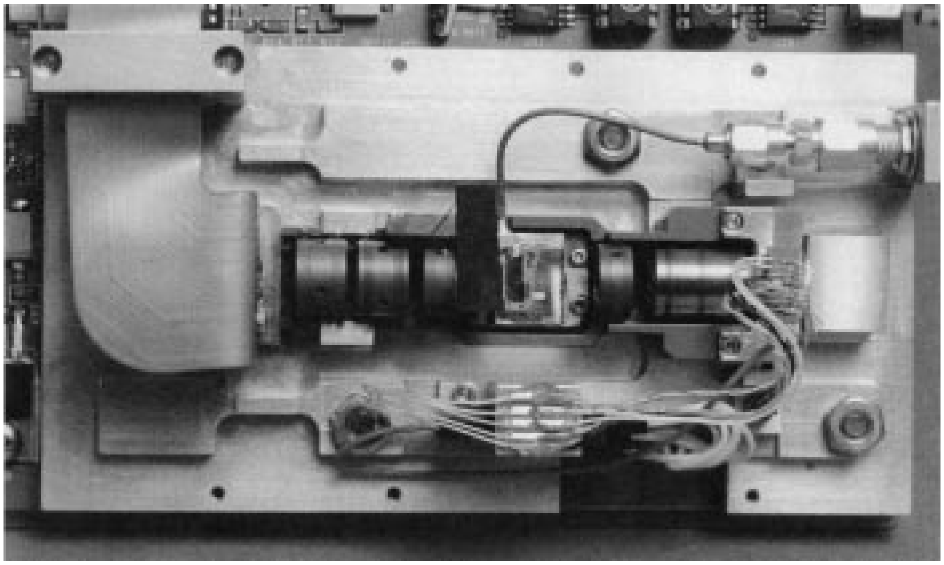

Fig. 12. Optical signal-processing assembly.

C. Optical RF Signal Processing

Optical channelization technology is being developed for wide-band processing as a compact economical means for performing high-resolution environment segmentation. Wide-band signal frequency demultiplexing is performed with optical diffraction and electronic signal detection and encoding. Functions performed by these optical processors include channelized correlation, convolution, and spectral processing.

Acoustooptic channelizers (Fig. 12) are based on Bragg diffraction of light. An optical modulator deflects light based on the microwave frequency of the input signal. The deflected light beams output from the Bragg cell are focused onto a detector array where light is detected to indicate energy in segments of the applied RF spectrum.

D. Digital-Receiver Technology

Digital-receiver technology currently operates well into the microwave regime, and the processing speed of digital devices is marching up Gordon Moore's curve, while size, weight, power, and cost continue to decrease [10]. For example, current commercial application-specific integrated circuit (ASIC) analog-to-digital converters (ADCs) in the 8-bit range can operate at sampling rates well in excess of 1.5 GHz. For EW applications, 1 GHz is typically IF. As the digital receiver technology doubles the sampling rate, more EW receiver functions will be performed by digital receivers.

The polyphase digital receiver architecture (Fig. 13) provides a highly efficient filter bank implementation, with identical linear phase filters that can be programmed into the field-programmable gate array (FPGA). The coefficient word size of finite impulse response (FIR) filter output grows in proportion to processing gain. The number of filters in a bank is determined by the amount of decimation and the size of a fast Fourier transform (FFT) that follows the filter bank. The FFT data output is in the form of parallel I/Q samples at the baseband of each channel.

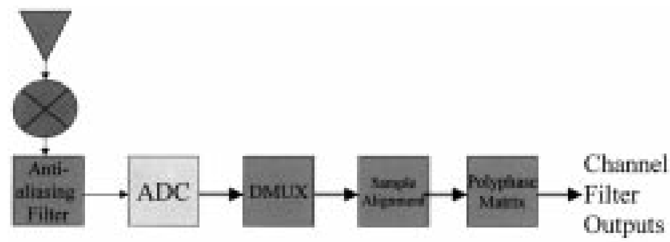

Fig. 13. Digital channelized receiver block diagram.

Major integrated investigations using these new technologies, such as the Advanced Multifunction RF Component (AMRF-C) demonstration, are being developed. The demonstration will verify the capabilities of each technology, provide engineering data, optimize ES architectures, and fine tune command and control configurations to improve the warfighter's ability to deal with the threats of modern weapon systems.

The channelizer output interfaces the ES digital signal processor (DSP) with a digital descriptor that characterizes an environment event. The event descriptor encoder accepts the channelized receiver output and constructs a digital descriptor word that characterizes the environment event. Specific characteristics of the event can include frequency, frequency modulation type, frequency-modulation characteristic, signal phase with respect to a system reference, phase modulation, phase-modulation characteristic, signal time of arrival, and signal amplitude. Measured signal characteristics are provided to the ES DSP for further processing.

The ES DSP accepts the receiver event descriptors and assembles associated descriptors to characterize signals and the ensemble of the signal environment. Individual event descriptors are assembled into event descriptors through correlation in time and event descriptor parameter space. Since environment events can exhibit agile characteristics from event to event, correlation of environment events into signal descriptors can require neural network algorithms in addition to statistical techniques to associate event descriptors and form signal descriptors. Correlation of *a priori* environment data with signal descriptor data provides additional information for the ES environment report. This ES report can include a shorthand signal notation, platform and system associated with the emitter, emitter identification, bearing angle and location, preferred EA approaches, as well as measured parameters of the signal.

Each decade, the intensity and sophistication of electronic combat increases. All means, including tactics, technology, and superhuman fortitude, are applied to prevail in the EW battle. Electronic and microwave technology are key factors in current EW engagements; the importance of these technologies is expected to grow to counter increasing weapons system sophistication. The microwave technology community is challenged with providing the technology base for EW systems necessary to overcome the formidable array of weapons systems in the current and projected geopolitical environment.

ACKNOWLEDGMENT

The author gratefully acknowledges illuminating and expert contributions to this paper by F. Klemm for offboard EW CMs information, S. Moroz for IR/EO weapons and EW technology, G. Weisbach for shipboard EW technology, A. Duckworth for definition of the EW environment, P. Griffith for EW MMIC technology description, S. Stitzer for magnetostatic-wave microwave processing submittal, and M. Thorton for microwave filter technology discussions.

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