Active Phased Array Antenna Development for Modern Shipboard Radar Systems

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Current and future Navy radar requirements are driven by rapidly evolving threats, including both cruise missiles and tactical ballistic missiles. To address these threats, array antennas will have to operate over wider bandwidths with enhanced sensitivity, higher radiated power levels, improved stability, and improved electronic protection to address reduced target radar cross-sections. In addition, there is a growing need for reduced array signatures and a practical need to control costs, including acquisition, operational, and support costs. Active phased array antennas have emerged as a fundamental technology for addressing these evolving Navy radar system needs. APL's Air Defense Systems Department has long been at the forefront of phased array antenna development for shipboard radar systems, and the Department is contributing to the development of active array antennas for the new generation of Navy radar systems currently under development. This article provides an overview of the emerging active array antenna technology.

INTRODUCTION

Shipboard radar systems typically must provide surveillance of thousands of angular locations and track hundreds of targets and guided missiles, all within relatively short reaction times. These requirements can be met only with phased array antennas that allow electronic repositioning of radar beams to widely diverse angular locations within microseconds. Over a 40-year span, APL's Air Defense Systems Department has participated in the development of phased array antennas for Navy radar systems.[1]

In addition to enhanced sensitivity, improved system stability will be required to detect low-flying cruise missiles in sea or land clutter. Wider bandwidths will be required to perform discrimination and target identification functions. At the same time that radar demands are increasing, there is a practical need to reduce acquisition and operation and support (O&S) costs, improve reliability, and reduce manning requirements. Active phased array antennas are emerging as a fundamental technology for addressing this evolving Navy radar system need, and APL's Air Defense Systems Department is playing a major role in these development efforts.

Although the concepts of phased array antennas are fairly straightforward, the factors that determine the design are extensive and even somewhat complex.

Design factors such as aperture sizing, pattern synthesis, and beamswitching speeds have changed little. On the other hand, solid-state component technology development has exploded over the last decade, exhibiting a continuing and significant impact on the design and performance of phased array antennas. The heart of an active phased array antenna is the transmit/receive (T/R) module. A T/R module at each radiating element provides power amplification during transmit and low-noise amplification during receive, as well as phase shift control for beamsteering. The emergence of gallium arsenide (GaAs) monolithic microwave integrated circuit (MMIC) technology has enabled the development of T/R modules with the required performance, excellent reliability, and acceptable cost in quantity production.

An active phased array radar can provide orders of magnitude performance improvement over its predecessor passive phased array radar, while at the same time improving reliability and reducing total ownership costs. Virtually all high-performance radars under development today employ an active array antenna. Navy radar development programs for which active phased arrays are a key enabling technology include the AN/SPY-3 multi-function radar, volume search radar for long-range surveillance, and advanced radars for Navy Theater Wide Ballistic Missile Defense. Other active array radars include the Theater High-Altitude Area Defense, National Missile Defense, and High Power Discriminator radars and the F-22 and Joint Strike Fighter fire control radars. Active array technologies have been used in commercial communications applications, including Iridium and Globalstar systems; however, these systems have not so far proven to be economically viable.

ACTIVE PHASED ARRAY ANTENNA OVERVIEW

To fully appreciate what active array technology has to offer, it is useful to first review the conventional, or passive, array approach currently deployed in several fielded

military radar systems. A radio-frequency (RF) block diagram of a typical passive phased array antenna is shown in Fig. 1a. A centralized transmitter, which generally consists of high-power microwave tubes (e.g., traveling wave tubes) or cross-field amplifiers, provides the power to the radiating elements through a high-power beamformer network. High-power ferrite or diode phase shifters are controlled at each radiating element to electronically steer the beam to the desired angle. In receive mode, the outputs of the radiating elements and phase shifters are combined using a low-power beamforming network. Typically, three simultaneous receive beams are provided to support monopulse tracking. Low-noise amplifiers (LNAs) are used to amplify the signal at the output of the beamformers. One of the
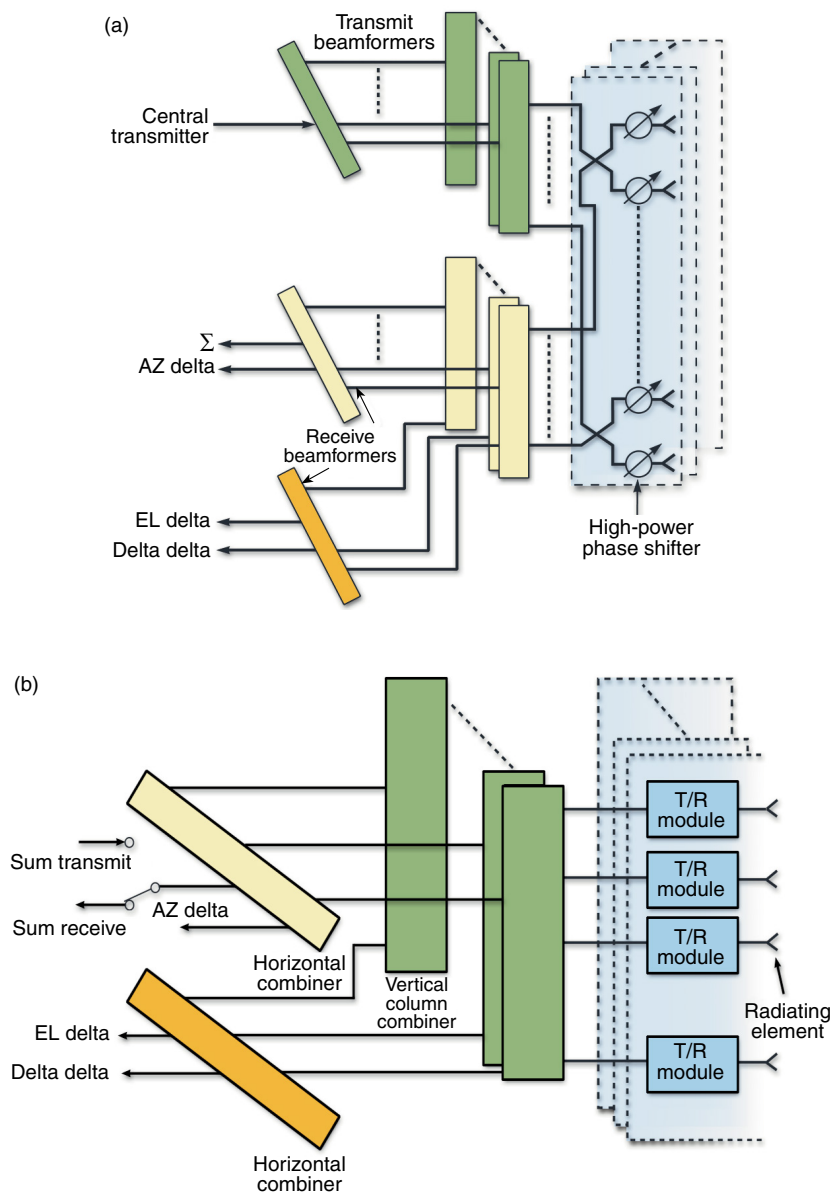
Figure 1. (a) RF block diagram of a passive phased array antenna. (b) Beamformer architecture of an active phased array antenna.

best examples of passive phased array radars is the AN/SPY-1 radar (Fig. 2), which has been in service for more than 20 years and is the Navy's highest-performing fielded radar.

Passive array systems have several inherent performance limitations and inefficiencies. For example, the transmit beamformer typically has significant losses, and the transmitter must generate a large amount of power to overcome these losses. In essence, a significant portion of the RF power generated by the transmitter is dissipated as heat before being radiated. High-power centralized transmitters usually employ microwave tube–based technologies, operate at lower duty factors, and have limited waveform flexibility. High receive beamformer losses, particularly when low sidelobes are required, significantly degrade receive sensitivity. Also, transmit noise from a centralized source is often a limitation in clutter-driven radar applications. Finally, high-power tube-based transmitters and their attendant high-voltage power supplies have lower reliability and higher maintenance and replacement costs than solid-state technology. This last issue is particularly important for shipboard applications that involve relatively long missions and a strong desire to avoid at-sea maintenance.

Evolving threats are driving the need for order-of-magnitude improvements in radar performance. Active array technology offers the capability of achieving the required performance improvements while at the same time offering improvements in reliability, maintainability, availability, and life-cycle costs. In active arrays, both transmit and receive functions are moved to the aperture by placing a T/R module at each radiating element (Fig. 1b). The T/R modules provide power amplification during transmit and low-noise amplification during receive, as well as amplitude and phase control for beamsteering and sidelobe reduction. Because this configuration places the power amplifiers and LNAs at the aperture, transmit an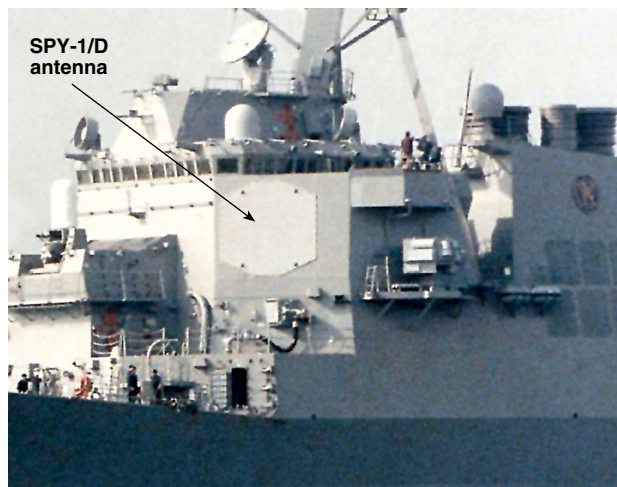d receive losses are significantly reduced, resulting in increased radar sensitivity for a given amount of generated microwave power.

Key radar system–level advantages of active phased arrays over passive phased arrays are summarized as follows:

- **Increased sensitivity.** Lower transmit and receive beamformer losses, coupled with the ability of solid-state T/R modules to operate at higher duty cycles than conventional tube-based transmitters, generally enables order-of-magnitude improvements in radar sensitivity.

- **Improved target detection in clutter.** In an active array, key sources of transmit noise and instabilities (e.g., T/R modules and power supplies) are distributed at the aperture. Consequently, their noise contributions do not add coherently in the same fashion as the transmitted signal, and their contributions to pulse–pulse variations undergo an averaging effect. The result is a significant improvement in the ability of an active array radar to detect small moving targets in sea or land clutter.

- **Improved waveform and pattern flexibility.** The multiple functions of detection, tracking, target identification, illumination, kill assessment, and missile communications can be better optimized by the waveform flexibility that the solid-state active array technology facilitates. Also, because both amplitude and phase control are provided by the T/R modules at the element level, radiation patterns are more readily optimized for the radar mode of operation, including the use of null synthesis techniques.

- **Improved wideband operation.** The solid-state technology employed by active arrays can support inherently wideband microwave frequency operation. In addition, active array architectures are conducive to the implementation of practical true time delay devices, which support wide-bandwidth, high range resolution waveforms and target imaging capability.

- **Reliable operation.** Solid-state technology and the associated low-voltage power supplies have inherently good reliability. In addition, the distributed nature of the T/R modules and power supplies allows the array to be designed so that operational performance requirements can be met when a few percent of the modules fail. Active arrays can be designed to be serviced at long periodic intervals, avoiding the need for at-sea maintenance. The increased reliability of active arrays is projected to result in significantly lower O&S costs over the lifetime of the array.

ACTIVE PHASED ARRAY SUBSYSTEMS

The following key parameters are typically specified for an active array:

Figure 2. SPY-1/D phased array antenna on DDG 51.

- Operating frequency and bandwidth
- Effective isotropic radiated power
- Scan coverage
- Beamwidths
- Sidelobe levels (all monopulse receive channels)
- Tracking accuracy
- Waveform parameters (duty, pulse width)
- System noise figure
- Third-order intercept
- Stability and phase noise
- Harmonic and spurious output
- Reliability, maintainability, and availability
- Manufacturing and life-cycle costs
- Prime power requirements and cooling
- Shipboard environmental requirements

The operating frequency, waveform parameters, and array performance requirements will vary depending on the particular applications served by the radar. The effective isotropic radiated power and beamwidth determine the number of elements and the required T/R module output power. The sidelobe levels determine the amplitude and phase characteristics of the T/R modules, aperture, and transmit and receive beamformers. The phase noise, stability, reliability, and maintainability requirements all influence the array architecture as well as the characteristics of the T/R modules and power supplies. The antenna cost and weight dictate the selection of technologies for different components

and, in conjunction with the environmental requirements, the array structure. The antenna cost, weight, and performance typically form a critical design trade space.

A block diagram of an active phased array radar system is shown in Fig. 3. An active phased array consists of a transmit and receive antenna aperture that includes the radiating elements, radome, and structure; T/R modules and associated control circuitry; RF beamformers; DC power distribution; and a beamsteering controller. Key features and fundamental design trades of these active array subsystems are addressed in the following paragraphs.

Transmit/Receive Modules

The fundamental building block and key enabling technology for active array radar antennas is the T/R module. Depending on the application, active arrays can contain hundreds or, more typically, thousands of T/R modules. These T/R modules have an important role in determining array performance; they drive many aspects of the packaging design and can account for as much as 50% of the cost of the active array antenna. GaAs MMIC technology is key to realizing the required microwave circuit density in the small footprint available at each antenna element. Semiconductor batch-processing production of GaAs MMICs is key to achieving the active array performance advantages at desired
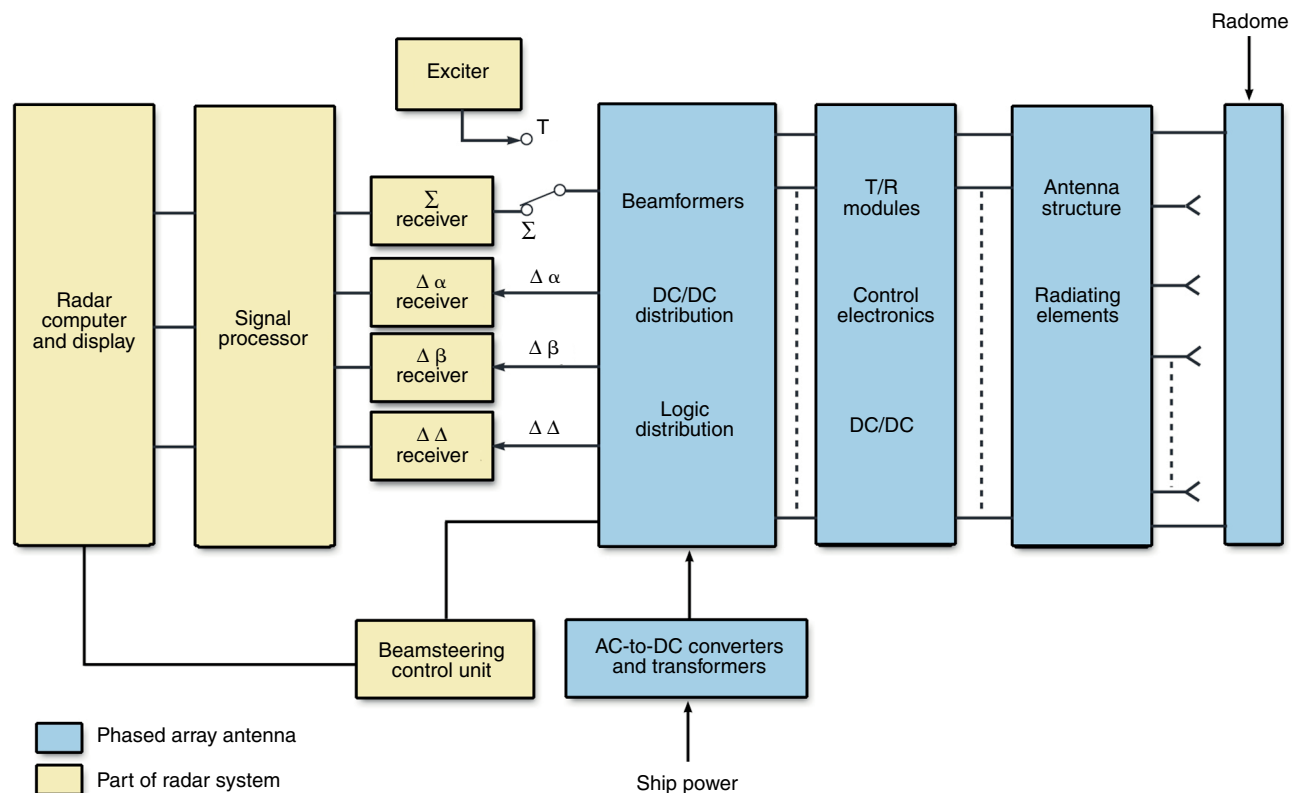

Figure 3. Block diagram of an active phased array radar system.

array acquisition costs. A typical T/R module is shown in Fig. 4.[2]

Figure 5 shows a block diagram of a typical T/R module. Each module contains a transmit path and a receive path. The transmit path consists of a phase shifter, a variable gain amplifier or attenuator (VGA), a driver amplifier, and a power amplifier. The power amplifier section may consist of several power amplifiers, typically two or four, where the output power of these amplifiers is combined to obtain the required output power for the radiating element. A circulator is used to provide the duplexing function and isolation between transmit and receive paths and to prevent load pulling of the power amplifier caused by variations in the antenna element's input impedance changes during beamscanning.[3] The receive path consists of a limiter, an LNA, a phase shifter, and a variable amplifier or attenuator. This module architecture provides an optimum performance compromise with respect to module noise figure, third-order intercept, and dynamic range.[4]

Voltage regulation and digital control circuitry are also often included in the T/R module. Local energy storage can be used to maintain transmit pulse current levels and satisfy rise-time requirements. Also, series regulators can be used for some or all internal voltages to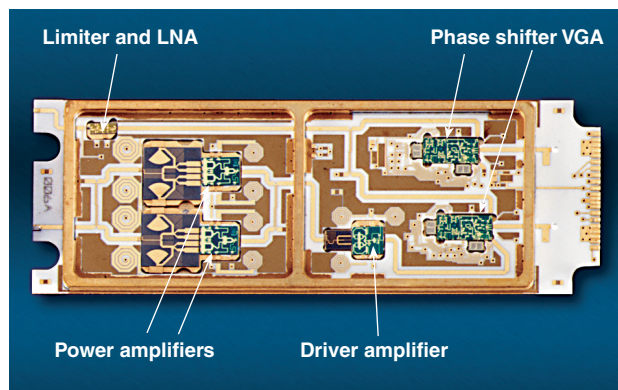 reduce power supply ripple and noise to acceptable levels to meet increasingly severe spectral purity requirements.[5] Low-resistance HEXFET switches are typically used to control the bias currents to the various amplifiers. Digital signals to control the phase shifter and attenuator are typically fed serially into the T/R module to reduce packaging complexity. This serial data stream is converted to parallel data with a shift register and clock signal. Memory may also be contained in the module to reduce the time required to switch between predetermined beam positions.
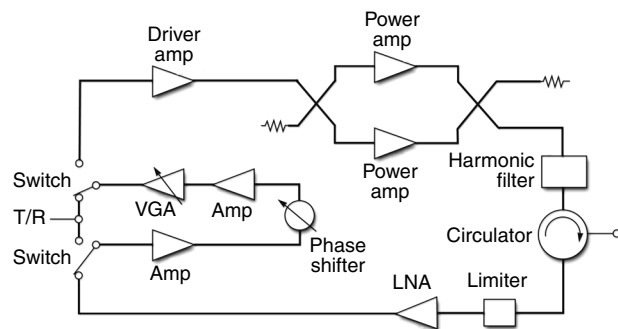
T/R module requirements are derived from the phased array antenna requirements and can vary significantly depending on the application. The following key parameters are typically specified for a T/R module:

- Operating frequency and bandwidth
- Output power
- Power-added efficiency
- Spurious and harmonic output
- Duty cycle and pulse characteristics
- Receive noise figure
- Receive gain and third-order intercept
- Number of amplitude and phase bits
- Amplitude and phase root-mean-square (rms) errors
- Mean time between failure (MTBF)
- Cost

The frequency, bandwidth, and output power are driven by the system application. A typical nominal output power for an X-band module, achievable with commercially available power MMICs, is around 10 W. Higher power levels are typical at lower frequencies. Power-added efficiency is an important parameter for minimizing the prime power requirements and cooling load of the active array. Depending on the technology used, transmit-power-added efficiencies on the order of 20 to 25% are typically achieved. LNA MMIC noise figures in the microwave regime typically range from 1 to 2 dB. Including losses and other effects, module noise figures in the 3- to 4-dB range are generally achievable. Modules used in low sidelobe applications require a higher number of phase control bits and lower amplitude and phase rms errors. Third-order intercept is an important parameter in mitigating interference from surface Navy radars where the radars, and thus the modules, are often operating in the vicinity of high-power radars on nearby ships. Because of the relatively long operating missions of surface Navy radars, module reliability is a critical factor in achieving low O&S costs and minimal maintenance actions. A T/R module should typically have an MTBF in the hundreds of thousands of hours.

Because of the large number of T/R modules in an active array, module production costs are critical to active array affordability. Module production costs can vary depending on performance, design complexity, production quantities, and other factors. Although

Figure 4. Photograph of a typical T/R module.

Figure 5. Block diagram of a typical T/R module.

the module cost breakdown can vary depending on the application, the typical cost breakdown of an X-band module (Table 1) is representative of current state-of-the-art X-band T/R modules. The cost of a T/R module consists of the cost of the semiconductors (MMICs), packaging, other components, assembly, and test. The MMICs are typically the most significant cost element. A more detailed T/R module cost discussion is provided in Refs. 6 and 7. The MMIC cost will increase with higher module output power.

Semiconductor cost is determined by wafer processing cost, wafer diameter, MMIC area, and yield. The wafer processing cost for GaAs is highly dependent on the volume of wafers produced by a foundry. Foundries typically can produce more than 20,000 wafers per year. However, production rates of at least 10,000 wafers per year are desirable to maintain low foundry overhead costs. Typical X-band T/R module production rates do not require a sufficient number of wafers to provide high foundry loading. One 4-in. wafer has enough area to supply the GaAs needed for more than 50 typical X-band modules. The production of 100,000 X-band modules per year would thus require less than 2000 4-in. wafers per year or less than 1000 6-in. wafers per year. Commercial volume using similar personnel and facilities is required to provide the low-overhead structure for cost-effective production of X-band T/R modules. Some GaAs producers have successfully achieved this product mix through high-volume sales to support wireless handset products.

Radiating Elements and Antenna Aperture

The critical design task for the radiating element is designing one that radiates efficiently, with good impedance match, over the operating frequency band and the scan volume of the array. Cost is a significant consideration because of the large number of radiating elements typically present. Because the performance of a radiating element is affected by mutual coupling with other radiating elements, the radiating element must be designed for the radiating environment rather than as an isolated element. The design process is usually iterative and consists of simulation using numerical electromagnetic modeling tools, fabrication of a waveguide simulator to verify performance at a selected scan angle,

and fabrication of a small test array (generally consisting of up to 100 elements) to verify full performance. A well-designed element will provide an element pattern on the order of $\cos^{1.25}\theta_s$ over the intended scan volume, where θ_s is the scan angle from array broadside.

The list of the different kinds of elements that have been used in array systems includes dipoles, microstrip patches, microstrip and waveguide slots, waveguides, horns, and flared notches (Fig. 6).[8] The choice of element depends on several factors, such as power handling, polarization, bandwidth, environmental conditions, feeding arrangement, and manufacturing cost.

Dipoles and patches generally have narrow bandwidth. The element bandwidth is defined in terms of loss in gain with respect to the center frequency. A flared notch element[9] (Figs. 6a and 6b), where an open circuited orthogonal central conductor excites the notches in the outer conductors, is typically used for wideband arrays. Bandwidths up to 6:1 have been demonstrated.[10] For a microstrip slot antenna, a cavity must be used behind each slot to restrict radiation to the front hemisphere. A microstrip slot radiator is shown in Figs. 6c and 6d.

For high-power radar arrays, variants of the rectangular or cylindrical waveguide radiating elements (Fig. 6e) are generally used. Waveguide arrays, though heavy, tend to have low loss and graceful scan degradation. Ridged waveguides can be used for wide-bandwidth applications. Single, double, and quad-ridged waveguides are shown in Fig. 6e. Quad-ridged waveguides extend these features to circularly polarized phased arrays. Often, the waveguide element is dielectrically loaded to match its impedance to free space. A wide-angle impedance matching (WAIM) sheet can be used to produce susceptance variation with the scan angle that partially cancels the array scan mismatch. WAIM sheets are less practical for shipboard environments because ice formation at the aperture is not permitted, and some kind of heating arrangement is required. For example, in the SPY-1 antenna, ice is inhibited by placing alumina windows on the individual waveguide radiators and heating these windows through conduction heating.
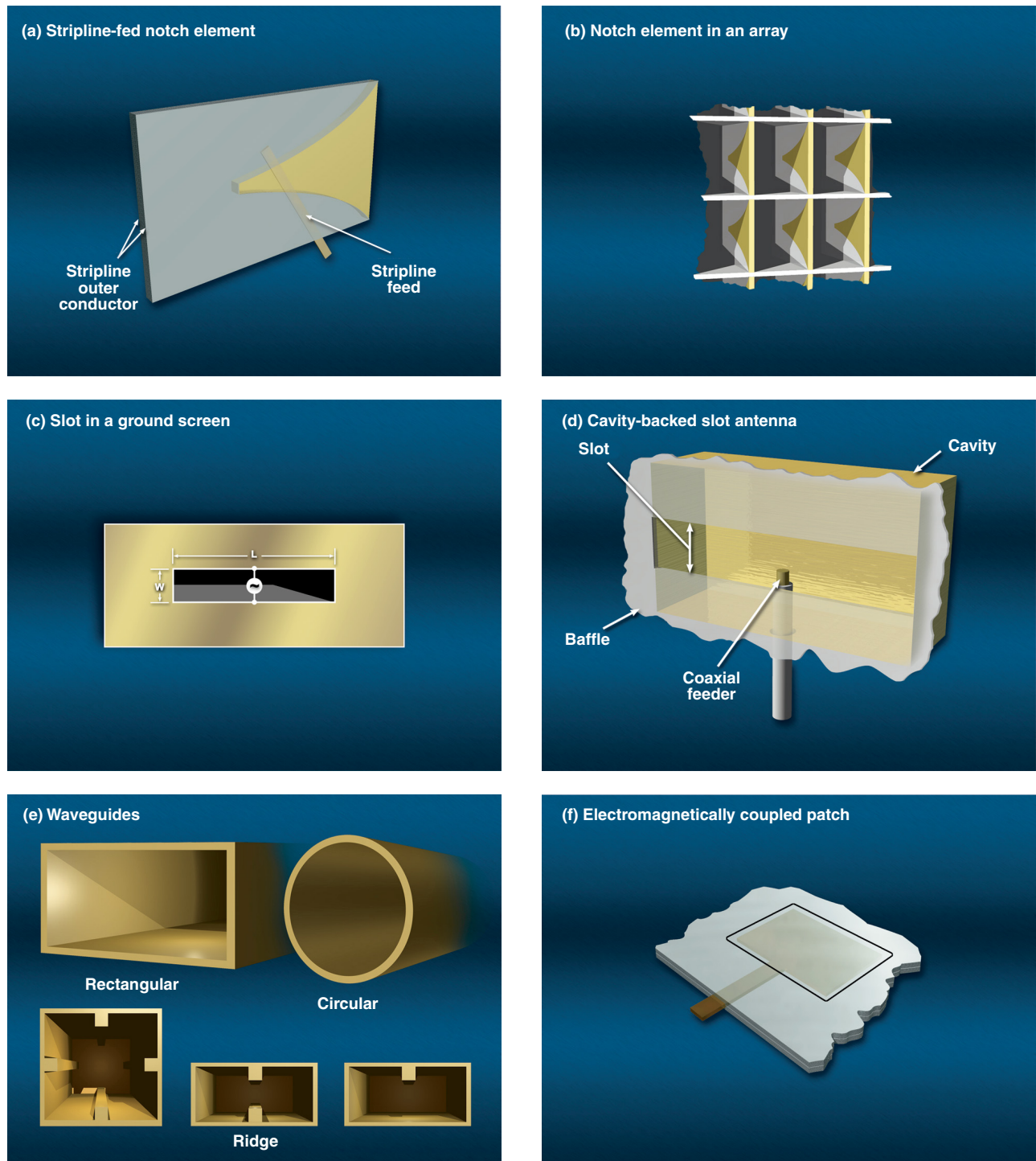
Microstrip patch elements (Fig. 6f) can be fabricated with low-cost lithographic techniques. The two most common feed techniques are an in-line microstrip feed and a coaxial probe feed. Patch elements are narrowband. For electromagnetically coupled patches in a phased array, the bandwidth can be increased to more than 15% by choosing patch dimensions, substrate thickness, and dielectric materials. Using double-stacked patches, essentially providing a double-tuned element, can increase the bandwidth further.

Radio-Frequency Beamformer Architectures

The RF beamformer plays a critical role in determining the radiation patterns, particularly the sidelobe

Table 1. Typical T/R module cost breakdown.	
Cost element	Percentage of T/R module cost
MMICs	45%
Package/substrates	25%
Digital/analog circuitry	15%
Assembly	10%
Test	5%

(a) Stripline-fed notch element

Stripline outer conductor

Stripline feed

(b) Notch element in an array

(c) Slot in a ground screen

L

W

(d) Cavity-backed slot antenna

Slot

Cavity

Baffle

Coaxial feeder

(e) Waveguides

Rectangular

Circular

Ridge

(f) Electromagnetically coupled patch

Figure 6. Radiating elements for phased-array antennas.

levels, of an array radar. On transmit, the RF beamformer distributes the input signals to the individual T/R modules. Typically, this is done so that each T/R module receives an identical input power level. Equal amplification in each T/R module then produces a uniform transmit aperture distribution that maximizes the transmit antenna gain.

In the receive mode, amplitude tapering across the aperture is typically applied to reduce the receive

sidelobe levels. Active array radars generally require low receive sidelobes to minimize susceptibility to jamming. The amplitude and phase error levels that can be maintained at the aperture determine the achievable sidelobes. The primary sources of error include the T/R modules and the RF beamformers. Phase shift control in the T/R module provides a mechanism for calibrating the module and beamformer phase errors. To obtain low residual and quantization phase errors to

support low sidelobe performance, as many as 7 bits are used in the digital phase shifter MMIC within the T/R module.

Passive array radars have similar requirements for low sidelobes. The amplitude control can be applied only in the receive beamformers in passive arrays, while the amplitude taper can be applied either in the beamformers or in the T/R modules in active arrays, as described next.

To obtain sufficient tracking accuracy, radars typically employ monopulse tracking techniques that require separate receive channels, or RF beamformer arrangements, for the receive sum, delta azimuth, delta elevation, and delta-delta channels. Each channel has an optimum amplitude distribution for low sidelobe performance. Also, because the channels are employed simultaneously, a single phase shifter in the T/R module cannot simultaneously correct phase errors in all monopulse channels, and often some compromise is made in the difference channel sidelobes relative to the sum channel sidelobes. There are many trade-offs in developing beamformer architectures for active array radars. Two common examples are discussed in the following paragraphs.

Figure 1b shows a simplified beamformer architecture of a monopulse active phased array antenna. In the receive mode, the radiating elements' outputs are first combined using column beamformers. The outputs of the column beamformers are then combined using horizontal beamformers to form the sum, azimuth delta, elevation delta, and delta-delta beams. The receive aperture weighting is applied in the T/R modules by using the attenuators or variable-gain amplifiers. Because the receive amplitude weighting is applied in the T/R modules, the transmit sum and receive sum beamformers have uniform distribution and are shared for the transmit and receive functions. The order of column and row combining can be interchanged.

The amplitude taper for an active array can also be applied in the beamformers rather than in the T/R modules, as shown in Fig. 7. Because transmit and receive amplitude tapers are different for this architecture, separate beamformers are required for the sum receive and transmit beams. Although the array with separate transmit and receive beamformers is more complex, it has a slightly lower receive noise figure. A lower antenna noise figure

is desired if the radar is to detect small returns. These two architectures have been analyzed,[11] and the results show that for a large active phased array antenna, the difference in the noise figure for the two is approximately 0.5 dB. The choice of common or separate beamformers is a function of beamformer complexity and antenna noise figure.

DC Power Distribution

Below-deck AC-to-DC converters convert a ship's AC power into DC power that is supplied to the arrays. The voltage into an active array typically ranges from 200 to 500 VDC and, as such, is stepped down to voltage levels required by the T/R modules (around 10 VDC or less) by DC-to-DC converters. The requirements for a DC-to-DC converter include voltage and current requirements of the T/R modules, output voltage droop and ripple, random noise, efficiency, dynamic step response, and enough input and output energy storage capacitors that the maximum droop due to load change during the longest transmit period meets requirements.

DC power can be distributed in an array using either a distributed or a centralized system. In a distributed system, a single DC-to-DC converter (power
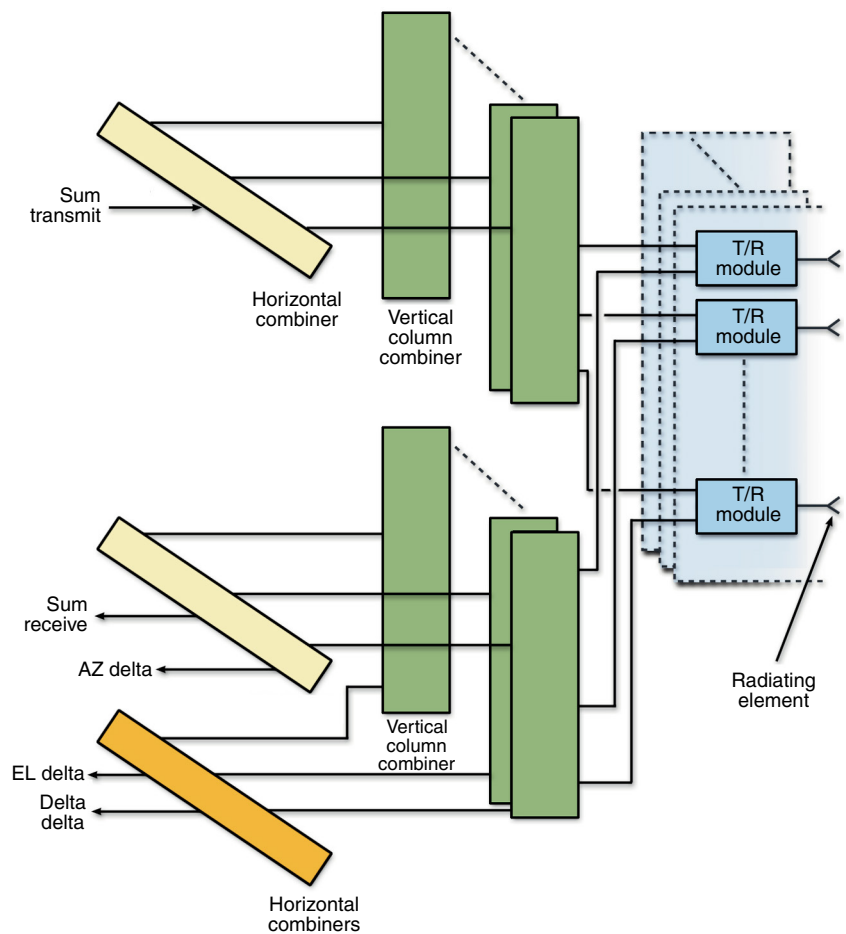

Figure 7. Beamformer architecture with separate transmit and receive beamformers.

supply) feeds a small group of T/R modules (typically two to eight) and DC-to-DC converters are distributed throughout the array, as shown in Fig. 8a. The DC-to-DC converters can be mounted on the same baseplate as the T/R modules. In the centralized power distribution system, a group of DC-to-DC converters are combined to feed a large section of the antenna. Redundancy is provided in each group of power supplies to increase reliability. The centralized power distribution is shown in Fig. 8b.

In both cases, the high-voltage DC is delivered to the converters using a low-current, high-voltage bus. In the centralized system, the low-power DC voltages are distributed throughout the array, requiring low-voltage, high-current buses. The converters convert high-voltage DC to low voltages required by the T/R modules, and voltage regulation is provided to generate voltages with very small ripple. Both approaches provide for improved clutter performance because of the uncorrelated random noise.[12] However, the DC-to-DC converters for the centralized system can be significantly larger than those of the distributed system and, to compensate for the impact of a smaller number of DC-to-DC converters on clutter performance, higher voltage regulation would be required.

The DC-to-DC converters can be either average power or peak power switching frequency converters. The switching frequency determines the size of the converter, as the converter size decreases with increasing frequency. The average power converters require storage capacitors to maintain the desired voltage droop. As the pulse width increases, the storage capacitance requirement increases, putting a physical limit on the length of the pulse. The other approach is to use a peak capacitor multiplying DC-to-DC converter. This converter has the unique advantage that the pulse energy can be stored on the primary high-voltage side of the converter, thereby resulting in a substantially smaller

energy storage capacitor. Both converters are comparable, and the choice of converter depends on pulse width, cost, and volume.

Beamsteering Controller

Transmit and receive beams in an active phased array antenna are steered by changing the insertion phase of the phase shifters contained in the T/R modules. An antenna beamsteering controller (BSC) generates the phase shift commands for all of the T/R modules. Generation of the phase shift commands can either be distributed throughout the array or performed in a centralized location. These two architectures are referred to as a distributed BSC and a centralized BSC, respectively.

In the distributed BSC architecture (Fig. 9a), a central controller generates simple commands such as scan angle, frequency, and timing.[13] The T/R module control electronics contain an application-specific integrated circuit (ASIC), electrically erasable programmable read-only memory (EEPROM), field effect transistor (FET) switches, etc. The phase settings for each T/R module are calculated by the ASIC, given the simple input commands and the module location. EEPROMs may contain linearization amplitude and phase tables for each T/R module. These data are module specific, stored in EEPROMs on the basis of module factory test results, and can be erased and reloaded with new data at any time. The data transfer rate from ASIC to T/R modules can be of the order of 20 Mbps.

In addition to sending the scan angle and frequency, the central controller sends a command to set the antenna in either transmit or receive mode by setting switches appropriately in the T/R modules. A local crystal oscillator generates the clock at each local group of modules. The clock speed determines the time it takes for commands to reach all T/R modules. Distributing the clock at the local level minimizes the noise, because the clocks are not synchronized. Because many
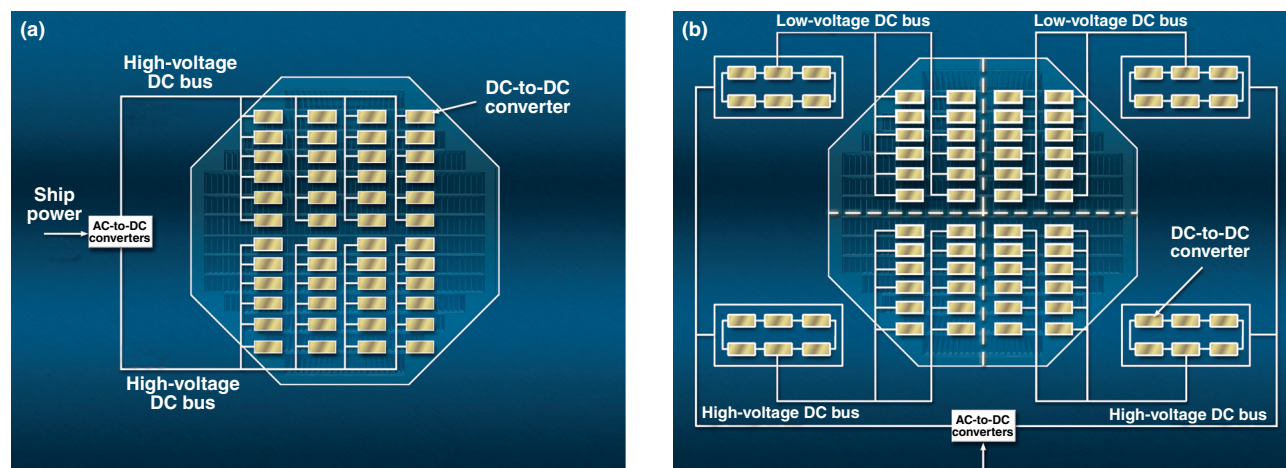

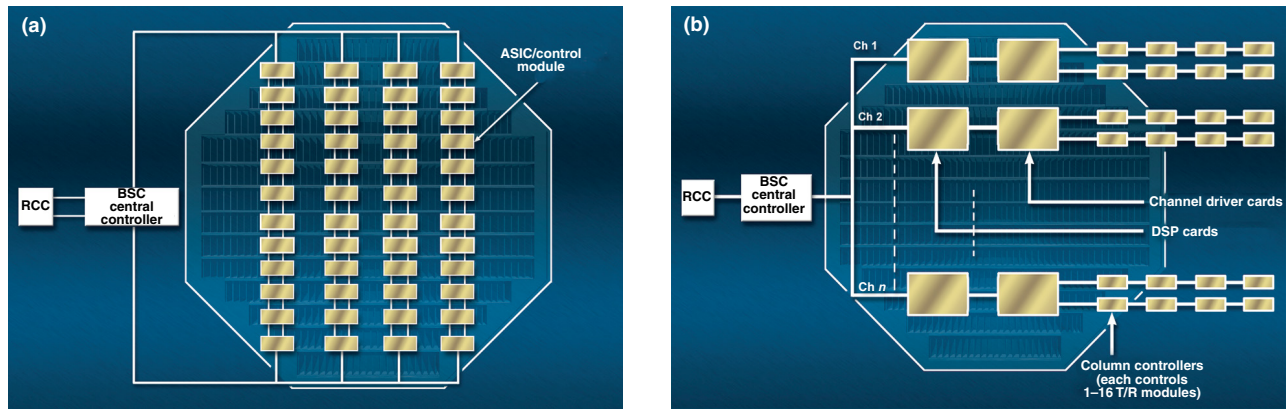**Figure 8.** (a) Distributed and (b) centralized power distribution architecture.

Figure 9. (a) Distributed and (b) centralized beamsteering controller architecture.

different beam-direction/gain-phase combinations can be stored in memory in advance, switching can readily be accomplished among various beams without recalculation within a single dwell.

In the centralized BSC architecture (Fig. 9b), most of the computations are performed in a central location and the data required by each T/R module are sent directly to the T/R modules or groups of T/R modules, such as lowest replaceable units (LRUs), using parallel buses. The central beamsteering controller may contain a number of digital signal processor (DSP) cards; each card is assigned responsibility for a specific group of T/R modules and stores all calibration values (linearization tables) for that group of modules. Each DSP card performs a set of beamsteering calculations for each T/R module in its group within a minimum pulse repetition interval (PRI). The PRI and the number of modules determine the total computation requirement. Several parallel processors may be needed to meet the requirements. The data that contain the phase and gain bits and that are sent over the control lines must be manipulated for final delivery to the T/R module. For the centralized BSC architecture, this function can be implemented in field-programmable gate arrays that can easily be reprogrammed to meet the requirements of a new T/R module.

The advantages of the centralized BSC include central processors that can be purchased commercially and reconfigured for different radar systems. The central control location requires a substantial data flow between the central control unit and the T/R modules. For a large active phased array, the data rates can range between 100 and 500 Mbps, requiring similar clock speeds. Fiber-optic data links may be appropriate at these speeds.

Either the distributed or the centralized BSC architecture can be adopted for a large active phased array system. Preliminary estimates show that the cost of these two architectures is very similar.

Mechanical Packaging

The predominant packaging considerations associated with the mechanical design of active phased array antennas include design for ease of maintenance, thermal management, packaging the DC power distribution system, RF beamformers, radiating aperture design/interface, and structural design. The overriding driver in what packaging options are available to the designer is the antenna operating frequency. As the frequency increases, element spacing decreases, requiring tighter spacing of the supporting electronics. Fortunately for the designer, higher-density arrays tend to have lower T/R module output power requirements; hence, the worst-case thermal design problems typically do not correlate with the worst-case packaging densities.

To optimize an array design for ease of maintenance, most of the active electronics are configured as LRUs, which can include T/R modules, DC-to-DC power converters, and various control/processor assemblies (Fig. 10). Reliability and system impact in the event of failure determine whether an assembly is designed as an LRU. System architecture, LRU reliability, and LRU cost define what is included within a given LRU. Fault isolation down to at least the LRU level is provided to minimize service time required during maintenance actions. Structural components, the coolant distribution system, RF beamformers, DC power distribution, and cabling are typically considered of sufficient reliability to be nonrepairable at sea.

Thermal design is critical for maintaining junction temperatures of the electronics at desired levels to support reliability requirements and maintain control of temperature-induced module-to-module phase errors. The T/R modules account for 70–80% of the heat generated within an array. Because of ever-increasing power density heat dissipation in modern shipboard active phased arrays, liquid cooling is normally required. The predominant cooling techniques in use today employ conduction away from the T/R module into liquid-filled coldplates or direct liquid flow-through cooling on individual LRUs. If the spacing allows electronics to be contained on one side of the LRU, the LRUs can be directly attached to the coldplates conducting across the large surface area opposite the components. Alternatively,
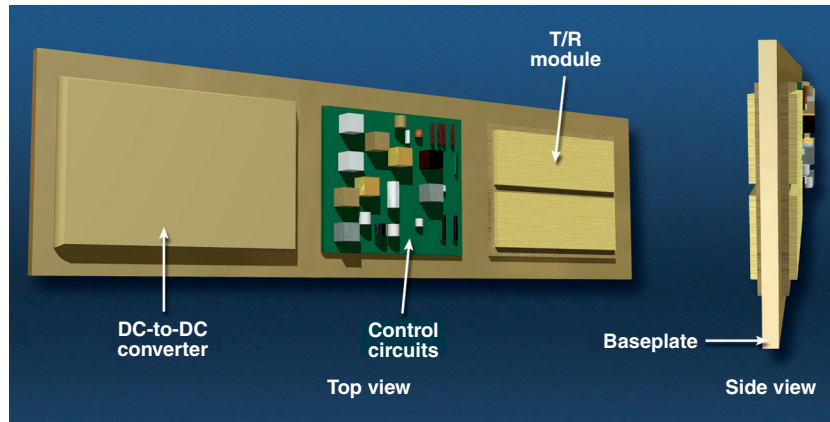
Figure 10. T/R module LRUs: components on both sides of a baseplate.

LRUs can be edge cooled. Figure 10 shows a typical edge-cooled LRU. As component power densities continue to increase, it may become necessary to mount the T/R modules directly to liquid-filled coldplates.

Because T/R modules exhibit phase changes with temperature variations, tight thermal control of the modules must be maintained across an array. Phase errors can be actively compensated for if the MMIC temperature is known. However, because of the difficulty in measuring the actual gate temperatures during various operational modes and duty cycles, this has not been shown to be practical. Current techniques focus on maintaining uniform coolant temperatures across the array and calibrating each element during one or more operating modes.

Maintenance requirements usually dictate that components not require removal to replace an LRU. In addition, maintenance must be performed from the back side (deckhouse interior) of the array, and therefore LRUs are inserted and extracted from the back of the array. It is imperative that RF beamformers, power distribution systems, control signal distribution systems, and their associated cabling be installed in a manner that allows ready access to the LRUs, and these elements must be designed to fit between the T/R module LRUs. This requires blind mate connections to the LRUs from the control, power, and RF distribution (and to liquid connections on liquid-cooled LRUs).

Two packaging configurations are shown in Fig. 11. In Fig. 11a, the T/R modules are mounted on a thermally conductive baseplate attached to the liquid-cooled mounting structure. This design is similar to the technique employed in air transportable rack equipment and allows components to be mounted to both sides of the baseplate. This technique offers a simple, easy-to-maintain packaging design that can accommodate tight element spacing. In addition, the coldplates become part of the antenna structure. Because of the increased thermal path length, the power dissipation capacity is somewhat power limited.

In the configuration shown in Fig. 11b, the T/R modules are mounted to one side of an LRU baseplate. The single-sided LRUs are mounted on a large vertical, fixed coldplate using wedge locks to press the baseplate against the coldplate. This configuration provides a large contact area to the coldplate and allows easy access to the LRUs; however, it tends to be better suited to larger element spacing, which allows LRU attachment by insertion on one side. The primary difficulty in this approach comes from the LRU-to-coldplate interface. To readily accommodate sliding insertion and extraction, the interface needs to be free of filler material. This requires tight tolerance control of both surfaces and makes achieving repeatable thermal resistance from module to module difficult. Alternatively, a phase-change–type interface material could be employed that would require heating the interface prior to extraction.
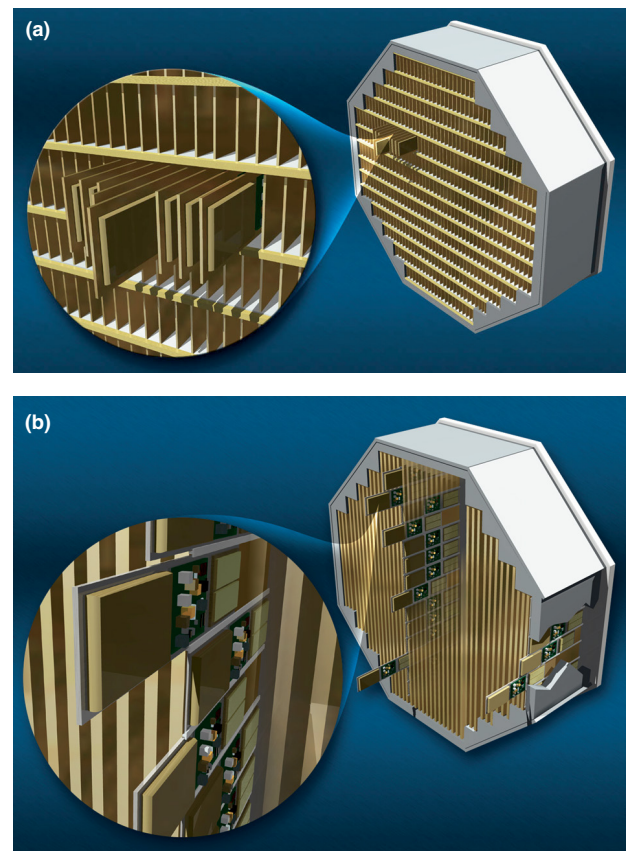
Figure 11. Antenna packaging assembly with (a) horizontal manifolds (edge-cooled LRUs) and (b) fixed vertical coldplates (one-sided LRUs mounted directly on both sides of the coldplates).

LRUs either must contain the radiating elements or must blind mate to the radiating elements on the array face. For low-sidelobe radar arrays, the latter is typically the case when the radiating elements are machined out of a faceplate to maintain tight element location tolerances. Overall mechanical alignment between the LRU and the radiating element requires tight control of large-tolerance stackups, and the resulting misalignment must be absorbed in the RF connector. There can easily be 15 to 25 tolerances, which combine to determine the radial float required in the RF connector. Because most floating RF connectors offer no more than 0.030 in. of radial float, it is necessary to use a combination of tight tolerances, statistical tolerancing methods, and occasionally specialized assembly fixtures to ensure proper alignment.

Structural design is a significant issue for shipboard active array radars. Traditionally the shipboard shock requirement (Mil-Std-901) has been the predominant structural design driver. For most antenna systems, floating platform barge testing is required. These tests impart a shock pulse on the order of 70 g at 11–14 Hz. A secondary consideration is to maintain adequate stiffness in the radiating aperture to ensure that array flatness requirements are maintained during operational sea states and shipboard structural vibrations. This flexural stiffness directly contributes to the array error budget and must be accounted for. Maintaining adequate flatness, particularly in larger, high-frequency arrays, will become increasingly difficult. One technique being explored is active measurement and compensation for deflection. In addition, error budgets must account for large-scale deflections of the ship's structural movement such as deckhouse or mast deflections.

RELIABILITY AND LIFE-CYCLE COST

Achieving life-cycle cost requirements is critical to the acquisition of any new active array radar system for the U.S. Navy. Life-cycle cost consists of development, acquisition, installation, O&S, and disposal costs, of which the acquisition and O&S costs are the main contributors. The keys to reducing life-cycle costs are minimizing the cost of spares and, through fault-tolerant design of the antenna architecture, minimizing the frequency of maintenance actions.

The reliability of the antenna is measured in two ways: MTBF and mean time between critical failures (MTBCF). The MTBF of a large phased array is quite low because of the large number of components. It therefore becomes critical to incorporate fault tolerance into the design.[14,15] Because of the redundancy of the electronics supporting each radiating element, active phased array antennas are inherently fault tolerant and can be readily designed to degrade gracefully.

Consequently they are projected to achieve an MTBCF sufficient to support ship deployment periods with no scheduled maintenance.

The key to reducing O&S cost is the reliability and redundancy of the individual LRUs. The LRUs must be optimally sized to minimize cost, parts count, and performance impact in the event of failure, yet be of sufficient size for array packaging and maintenance access considerations. Antenna acquisition costs are primarily driven by the T/R module; however, LRU assembly and DC-to-DC converter costs can also be significant. Key to reducing these costs is attention to produceability and elimination of touch labor in the assembly. Because of the highly redundant nature of the architecture, many LRUs are produced in sufficient quantities to warrant true design for production.

Because of the combination of an inherently redundant architecture and highly reliable solid-state electronics (notably T/R modules), active arrays are projected to provide improved reliability and reduced O&S costs relative to conventional array radar systems.

CONCLUSION

Active array antennas have emerged as a fundamental technology for addressing evolving surface Navy radar system needs. New shipboard active array radars currently under development include the AN/SPY-3 multifunction radar, volume search radar for long-range surveillance, and developmental radar concepts for Navy Theater Wide Ballistic Missile Defense. Largely as a result of active array technology, these new radars are projected to provide dramatic performance improvements as well as improved reliability and reduced O&S costs relative to conventional radar systems.

This article presented an overview of the key aspects of an active array and its various subsystems. The current state of the art was described, with particular emphasis on the critical T/R module technology. T/R module cost considerations were also addressed, given the significant focus on achieving affordable radar acquisition costs.

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