Beamformer Architectures for Active Phased-Array Radar Antennas

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***Abstract*— In active phased-array antennas, the transmit and receive functions are distributed at the antenna aperture using transmit and receive (T/R) modules. The use of T/R modules provides a significant improvement in antenna performance and flexibility in the choice of array architectures. In this paper, we present a review of various beamformer architectures for active phased-array antennas. This review is limited to corporate-fed active phased-array antennas for radar applications, as the general discussion to include all phased-array types is too broad for any one presentation. Beamformer architectures for narrow and wide bandwidth arrays, including the choice of applying an amplitude taper in the T/R module or beamformer network are discussed. Beamformer architectures that increase antenna reliability are also presented.**

***Index Terms*— Active arrays, phased arrays.**

I. Introduction

THE requirements for target detection radars operating in complex threat environments have driven system designers to use active phased-array antennas. Transmit/receive (T/R) modules are key elements in any active aperture system. Active phased-array antennas use a T/R module for each radiating element. The transmit power is distributed at the aperture, eliminating the central high-power transmitter needed in passive phased-array antennas.

Since the RF power and low-noise amplification in an active phased array are distributed at the aperture, the effect of losses in the transmit and receive beamforming networks is greatly reduced. Sufficient transmit gain in the T/R module allows a very low RF input power to the antenna. In receive, a high-gain low-noise amplifier (LNA) reduces the noise contribution from secondary stages of the T/R modules and beamformers. By reducing the impact of transmit and receive beamformer losses, large active phased-array antennas provide increased radar sensitivity in the range of 8–12 dB compared to passive arrays. In addition, T/R modules can provide wider bandwidth and higher average transmit power as compared to passive phased arrays with central tube transmitters.

Radar systems often use monopulse techniques to derive angle tracking information from a single-echo pulse, requiring a separate receive beamformer for each of the three monopulse beams, viz., sum (Σ), elevation difference (EL DELTA), and azimuth difference (AZ DELTA) [1]. Corporate beamformers are generally preferred in phased arrays that need wide instantaneous bandwidth and good impedance match. The beamformers can be constructed either in waveguide or stripline. Manifold insertion loss may range from 2 to 3 dB for an all waveguide to as high as 8 dB for an all-stripline beamformer. For wide-band operation, stripline medium is used. A general discussion of beamforming feeds for various type of antennas is provided in [2] and an overview of array architectures is provided in [3], [4]. In this paper, we focus on the beamformer architectures for active phased-array antennas.

High-performance radars use pulse-doppler detection modes to separate small signals from large levels of clutter received [1]. The system dynamic range from the T/R module through the A/D converter has to be large enough to handle the clutter return and small target signal. Therefore, the receive channel architecture needs to consider the entire receiver chain. The gains of various components in the receive chain must be set to meet the system requirements. The transmit channel architecture is also affected by system desires to radiate a transmit beam that has a sidelobe structure different from the receive beam sidelobes. Since very low sidelobes are not critical for the transmit beam, a uniform distribution is typically used that results in higher gain in transmit than receive and increased radar range. This may necessitate the use of separate transmit and receive manifolds in order to preserve low receive sidelobes and high transmit gain.

For active phased-array antennas, the receive amplitude taper can be generated either by the T/R module or receive beamformer. The decision to provide the amplitude taper in the T/R module or receive beamformer depends on the receive noise figure, input third-order intercept (TOI) and dynamic range requirements. The portion of the receiver chain behind the array manifold, which processes the combined receive output power of all the T/R modules needs to have high dynamic range. Its noise figure impacts the overall system noise figure. System architecture tradeoffs of input third-order intercept and noise figure may or may not allow arbitrarily high gain in the T/R module to swamp poor noise figure at the receiver [5].

We first review beamformer architectures for passive phased-array antennas used in radar applications in Section II. In passive phased arrays, the transmit power from a single transmitter is distributed to the array elements through a passive beamformer network. Separate transmit and receive beamformers are used for the transmit and receive beams. The amplitude taper to provide low receive sidelobes is provided in the receive beamforming network. The beamforming networks for passive phased arrays form the basis for the discussion of beamformer architectures for active phased-array antennas.

If the receive amplitude taper is applied in the T/R module with either a variable gain amplifier (VGA) or attenuator, the

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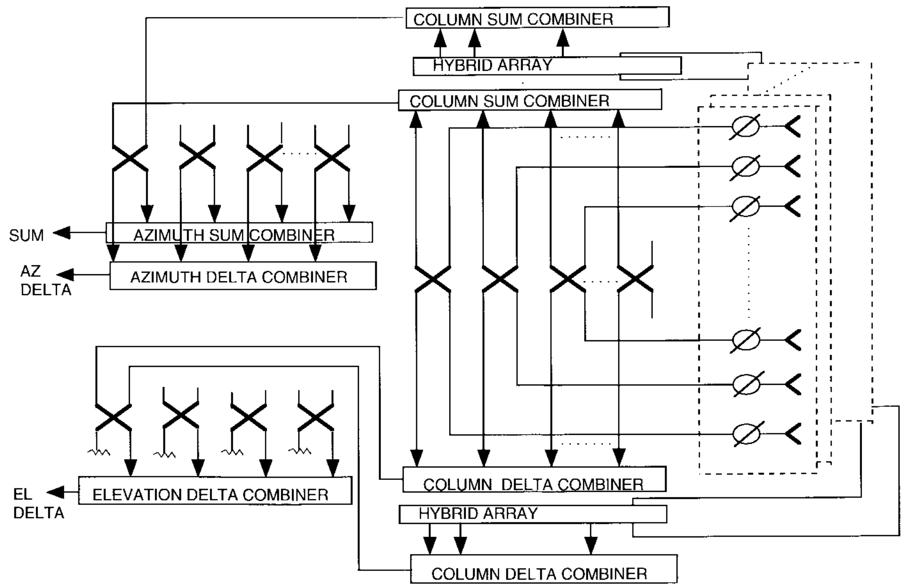

Fig. 1. Receive beamformer architecture of a passive phased-array antenna.

receive beamformer architecture can be greatly simplified [6], [7]. This beamformer architecture is discussed in Section III. In Section III, a receive beamformer architecture with separate amplitude and phase control for each of the monopulse beams is presented. This architecture results in a very simple, low-cost beamformer network where amplitude and phase errors in the beamformer network are not critical, as these errors can be calibrated in the T/R module for each of the monopulse beams independently. Therefore, the sidelobe performance in each of the three monopulse beams can be optimized.

In Section IV, a tradeoff between two receive beamformer architectures for antenna performance in terms of noise figure, input TOI, and dynamic range is presented. In the first beamformer architecture, the receive amplitude taper is applied in the T/R module, and in the second beamformer architecture, the receive amplitude taper is applied in the beamformer. Since the transmit and receive amplitude tapers are different, the second architecture requires separate beamformers for the sum receive and transmit beams. On the other hand, a common transmit and sum receive beamformer can be used for the first architecture.

Since active phased-array antennas contain large numbers of active components, the antenna performance degrades gracefully as components fail over time. In addition to T/R modules, active phased arrays may contain large numbers of power supplies or dc to dc converters; each dc to dc converter feeds a group of T/R modules. The array architectures that provide higher reliability are discussed in Section V. By employing fault-tolerance in the design of an antenna architecture, the antenna reliability can be increased so that replacement of failed components can be avoided for an extended period of time.

In Section VI, the beamforming networks for wide-band active phased-array antennas are presented. To increase the instantaneous bandwidth of an array, the aperture is divided into subarrays, and a time delay unit is used behind each subarray to provide true-time delay for phase shift.

II. Beamformer Networks for Passive Phased-Array Antennas

Radar systems often use monopulse techniques to derive angle-tracking information from a single echo pulse. This is accomplished by generating two or more, usually three, antenna beams [1], so that the simultaneously received echoes from the multiple beams can be compared. A phased-array antenna that generates three simultaneous beams in order to support monopulse operation requires a separate beamformer for each of the three beams.

High-performance phased-array monopulse antennas in current use have several thousand radiating elements. A beamformer for use with such an antenna array must, therefore, include several thousand inputs and may require different amplitude weighting for signals applied to each input. The amplitude weighting is provided in order to control the sidelobe performance of the beams.

A simplified block diagram of a typical receive beamformer for a monopulse phased-array radar antenna is shown in Fig. 1. Signals from elements in each column equidistant from the array centerline are fed to the column beamformers of sum and difference hybrids where the two vector signals are added and subtracted. The sum and difference outputs are separately weighted and combined to form one elevation sum and one elevation difference signal per column of radiators. The column sum and difference signals are combined symmetrically about the array centerline in the horizontal beamformers to form the three monopulse signals. To obtain low sidelobes in the receive mode, a Taylor weighting is applied in the sum beamformers. To obtain Taylor weighting in two dimensions, the weighting in the column and horizontal beamformers is such that their multiplication results in the desired two-dimensional weighting function. Similarly, a Bayliss weighting is applied in the beamformers to provide low sidelobes in the difference beams.

A typical beamformer requires a large number of coupler designs that are selected to provide the necessary amplitude tapers with the designs modified after test to compensate for coupler interactions and manufacturing errors. The amplitude and phase errors across the aperture contribute to the sidelobe level for each of the simultaneous beams. The random error contribution to sidelobe level is largely set by design, manufacturing, and testing technology. To obtain low peak and rms sidelobes, phase and amplitude errors must be reduced and correlation of errors between elements must be minimized. The correlated errors can be minimized by measuring the phase errors in the feed network to each element of the array and using the phase shifters to compensate for that error. This approach reduces the effective element phase error to that of phase shifter quantization and measurement errors. The residual error after correction is a function of bandwidth, random errors in the phase shifters, and tracking and alignment errors between beamformer channels.

The effects of the resulting amplitude and phase errors depend on where they occur in the combining network. The elements that share a given error act together as a subarray. The effect of the error has gain due to the directivity of the concerted action of the elements within the correlation interval. Therefore, correlated errors are multiplied by the number of elements affected by the error.

While the phase errors in the beamforming network for the sum beam can be corrected by the phase shifters, such errors cannot be simultaneously corrected for the difference beams with only a single-phase shifter per element. Since the phase errors for the difference beamformers cannot be corrected simultaneously for monopulse operation, the phase errors for the difference beamformers in passive phased arrays are larger than the sum beamformer and the achievable sidelobe level for the difference beam is generally higher than for the sum beam.

The interconnections within the beamformer, which lie between the radiating element and the common output port of the beamformer, must be carefully phase controlled so as not to introduce errors. When three such beamformers are used—one each to produce a sum (Σ), azimuth difference (AZ DELTA), and elevation difference (EL DELTA) beam—the insertion phase of the sum and delta beamformers must track each other closely so that the desired performance for monopulse operation is achieved under all operating conditions. For example, phase errors between sum and delta beamformers can result in beam pointing angle error.

The complexity of the beamforming arrangement of Fig. 1 is apparent. Additional complexity arises because of the amplitude weighting of the signals relative to each other in each column and from column to column in order to achieve the appropriate sidelobe level for both elevation and azimuth beams. Even if phase shifters are set correctly, assuming equal phase signals arrive at the phase shifters, cumulative phase errors through the combiners and hybrid arrays may adversely affect performance. In this regard, it should be noted that the actual physical lengths of interconnecting cables must nearly be equal for wide bandwidth signals.

III. Beamformer Networks for Active Phased-Array Antennas

In active arrays, both transmit and receive functions are placed at the aperture. This function is achieved by using a transmit/receive module for each radiating element. Each T/R module contains a transmit chain consisting of power amplifiers to provide power to each radiating element and a phase shifter and a receive chain consisting of a low noise amplifier, phase shifter, and amplitude control. Since the transmit power is distributed at the aperture, there is no central high-power transmitter. Placement of power amplifiers and low-noise amplifiers at the aperture eliminates the transmit and receive beamformer losses, resulting in increased radar sensitivity of 8–12 dB for large phased arrays. In addition, the solid state technology used in the T/R modules can provide wider bandwidth and higher average power by operating at a higher duty than tube technology.

For active phased-array antennas, the receive amplitude taper can be provided either in the T/R module or the beamforming network. When the amplitude taper is generated in the modules, the resulting beamformers are simple uniform weight beamformers. However, the amplitude taper can also be provided in the beamformers as in passive arrays. In this section, we will discuss beamformer architectures with amplitude taper provided in the T/R modules. In the next section, the two beamformer architectures will be compared for their dynamic range and noise figure performance.

Since there is no central high-power transmitter in active arrays, the transmit beamformer can be constructed using low-power transmission lines fabricated from printed circuit boards and can also be shared with the receive sum beamformer.

Fig. 1 illustrated the use of column sum-and-difference hybrids and combiners to form column-sum and column-difference signals and further used sum-and-difference hybrids and combiners to form the sum (Σ), AZ DELTA, and EL DELTA beams. Fig. 2 shows a simplified block diagram of a monopulse active phased-array antenna architecture in which each T/R module associated with the antenna element has three receive outputs. The architecture in Fig. 2 consists of three beamformers—one each for sum, elevation delta, and azimuth-delta receive beams. The transmit beamformer and sum receive beamformers are common and these two functions are shared by this beamformer using a switch.

Fig. 3 is a simplified block diagram of a T/R module with multiple outputs [7]–[9]. The transmit chain consists of a phase shifter, a low noise amplifier, a variable gain amplifier (VGA), a driver amplifier, and a power amplifier. The power amplifier may consist of several power amplifiers, typically two or four, where the output power of these amplifiers is combined to obtain required output power. Broadcasting of harmonics of the transmit signal is reduced by a harmonic filter. The receive chain consists of an LNA proceeded by an amplitude limiter. A circulator is used to provide the duplexing function and isolation between transmit and receive signals. The output of the LNA is divided equally into three signals using a three-way power divider. These three signals go through a phase shifter, low-noise amplifiers, and a VGA, and the outputs are connected to the three monopulse beamformers: sum, elevation delta, and azimuth delta. In addition, the sum receive channel is also shared with the transmit beamformer using a double-pole double-throw (DPDT) transfer switch as shown in Fig. 3. This module architecture provides optimum performance with

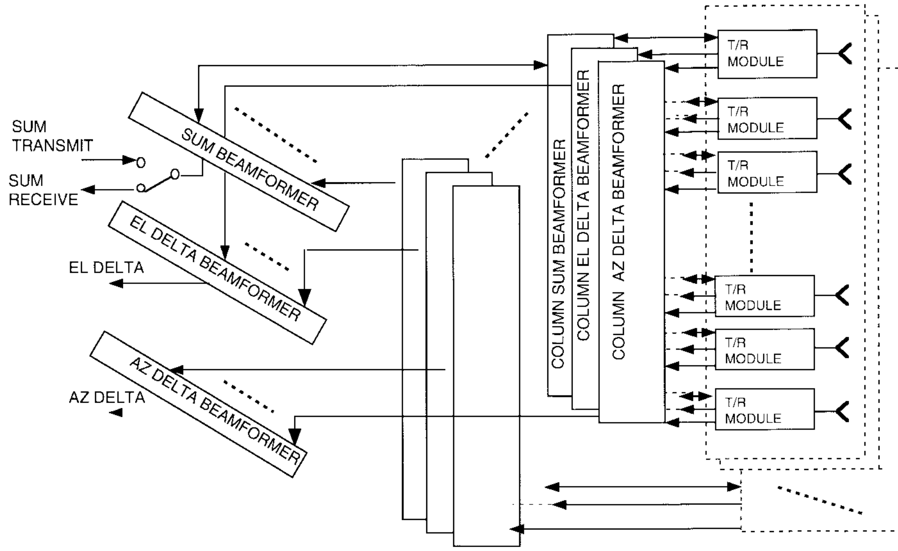

Fig. 2. Beamformer architecture of an active phased-array antenna with three independent receive beams.

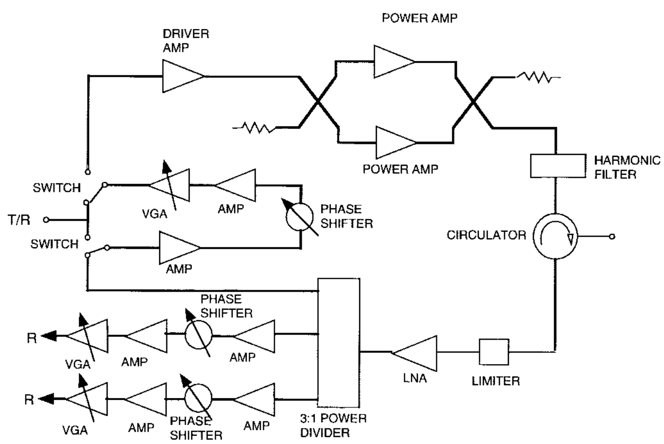

Fig. 3. Block diagram of a T/R module with three receive outputs.

respect to module noise figure, TOI, and dynamic range [10]. There are several advantages to this architecture compared to a more conventional common phase-shifter architecture: 1) it minimizes the number of components since gain stages are shared between transmit and receive; 2) the receive dynamic range is maximized since gain stages are distributed before and after the lossy phase shifter; 3) the VGA can be used for programmable transmit aperture as well as receive; and 4) the shared components can be designed as an integrated chip using a versatile high-yield monolithic microwave integrated circuit (MMIC) process without degrading module performance.

The beamformer architecture of Fig. 2 has the salient advantage that the beamformer designs are not critical and need not have connections made in matched pairs equidistant from the center lines of the array. Thus, there may be a great saving in cable length and weight and a reduction in criticality of the phase through various paths. The phase shifts of the phase shifters of each T/R module can be adjusted to optimize the phase shift through a particular path connected to the output port of that module. The performance in either transmission or reception can, therefore, be optimized separately for each of the sum, AZ delta, and El delta beams. For the difference beams, an extra 180° phase shift can be added to the elemental outputs from the selected half arrays. The VGA's can be adjusted not only to correct amplitude errors in the beamformer, but can provide the amplitude taper required to reduce the sidelobe level. The beamformers can be designed using standardized coupling values rather than coupling values that are customized to provide the desired amplitude weighting. At each operating frequency of the array, the phase shifters and variable gain amplifiers can be programmed with the amplitude and phase required to correct the errors that occur at that frequency.

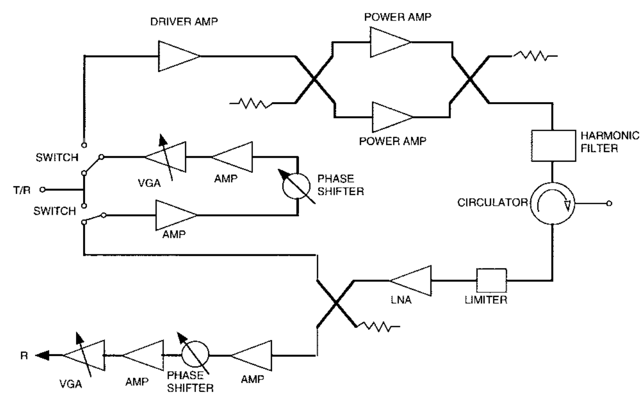

Fig. 4. Block diagram of a T/R module with two receive outputs.

Since, for the beamformer architecture in Fig. 2, the residual phase and amplitude errors in all three beamformers can be corrected using VGA's and phase shifters in the T/R module, the achievable sidelobe performance for all three monopulse beams is the same, a significant improvement over the passive architecture of Fig. 1 where the achievable sidelobe level for the difference beam is higher than for the sum beam. Accordingly, the limiting factor in the sidelobe performance of such an array is only the amplitude and phase performance of T/R modules together with the long-term stability of the components.

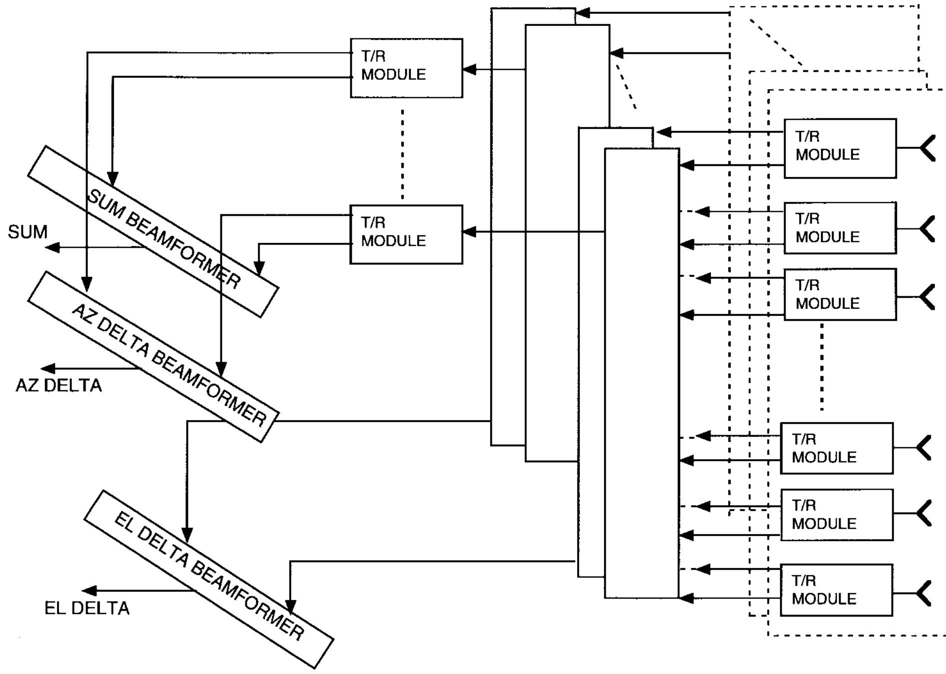

Fig. 5. Beamformer architecture of an active phased-array antenna with two independent receive beams.

A disadvantage of the arrangement described in Figs. 2 and 3 lies in the number of phase shifters and VGA's and complex controls that may therefore be required. A compromise between the beamformer architecture of Fig. 1 with a single-phase shifter for multiple beamformers and the beamformer architecture of Fig. 2 with a single-phase shifter for each beamformer of the array, may be the set of two phase shifters for three beamformers. Fig. 4 illustrates a T/R module architecture with two phase shifters resulting in two independent receive channels. Fig. 4 differs from Fig. 3 in that the low-noise amplifier has its output coupled to a two-way power divider. Fig. 5 is a simplified block diagram of an array antenna using the T/R module of Fig. 4. One of the outputs of the T/R module is coupled to an elevation-difference beamformer illustrated in Fig. 4. This beamformer is similar to the elevation-difference beamformer of Fig. 2, which combines the elevation signals from T/R modules in a column to provide a column elevation difference signal.

The uppermost or sum outputs from each T/R module in a column are connected to the inputs of a sum-column beamformer. From the single output of the column beamformer both sum and azimuth beam must be generated. The desired pair of beams are generated from the output of the column beamformers by coupling these outputs to a further array of T/R modules. Each T/R module receives a signal from the corresponding column in the receive mode and divides the signal into two signals and applies them to a sum beamformer and an azimuth beamformer. This arrangement has the advantage of relative simplicity compared with the arrangement of Fig. 2, while maintaining the advantage of substantial control over the three antenna beams. The column T/R module in Fig. 4 is similar to the T/R module in Fig. 3, but has only two receive channels and the transmit channels have a lower transmit out power since the final power amplification takes place in the T/R modules at the antenna elements.

IV. Impact of Beamformer Architecture on System-Noise Temperature

In this section, two common receive beamformer architectures, used in active phased arrays to generate low sidelobe sum patterns, are compared for architectural complexity and their performance in terms of noise figure, input TOI, and dynamic range. In the first beamformer architecture, the receive amplitude taper is applied in the T/R module, and in the second beamformer architecture, the receive amplitude taper is provided in the beamformer [11]. Since the transmit and receive amplitude tapers are different in the second architecture, separate beamformers are required for the sum receive and transmit beams. On the other hand, for the first architecture, a common transmit and sum receive beamformer can be used.

Figs. 6 and 7 show two popular corporate beamforming architectures; they differ in how they form the sum channel receive weighting. For comparison of these two architectures, only sum beamformers are considered. In Fig. 6, the weighting is implemented actively with the T/R modules, while in Fig. 7, nonuniform (unequal) combiners are employed within the beamformer to passively create the low sidelobe weighting. In general, the passive weighted architecture provides the lowest system noise figure and highest output intercept point, while the active weighted architecture is the easiest to construct and produce. It is beneficent to gain more insight into the differences between the two architectures. Toward this end, a detailed comparison of these two beamformers in terms of their architectural complexity and receive performance (noise figure and output intercept point) is presented.

The active-weighted architecture of Fig. 6 has the advantage of using the same beamformer for transmit and receive. In the

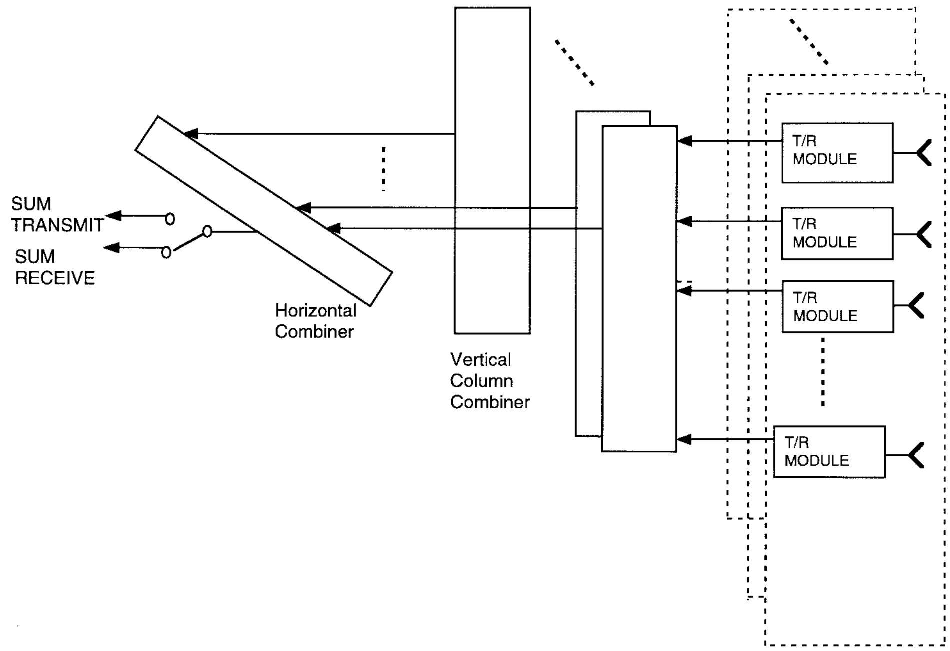

Fig. 6. Active-weighted beamformer architecture.

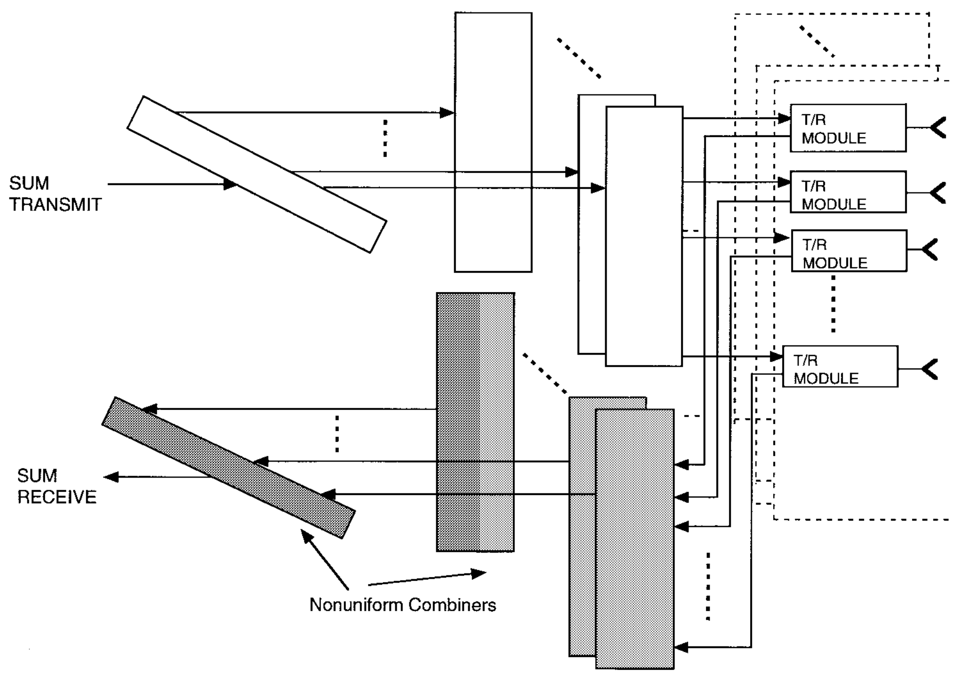

Fig. 7. Passive-weighted beamformer architecture.

Fig. 6, an M-element array of T/R modules is backed by a combiner for each column of the array and the columns are summed by a single horizontal combiner to give the sum-channel receive output. On transmit, the T/R modules are set to maximum gain and output power and, on receive, the low sidelobe taper is applied by varying the gain of the receive VGA's in the T/R modules.

The passive-weighted architecture of Fig. 7 is more complex. It requires separate beamformers for transmit and receive operation. The transmit combiners are uniform. However, on receive, all T/R module VGA's are set to maximum gain and the low sidelobe taper is provided in the receiver combiners by using nonuniform beamformers. For a rectangular array with a separable amplitude distribution function, the vertical combiners in each column are identical; however, for a circular array, each column will require a different combiner.

Although the passive-weighted array is more complex, it has a lower receive noise figure and higher intercept point than the active-weighted array. A low antenna noise figure is critical if a radar is to detect small returns, while a high antenna TOI is essential when there are big scatterers such as clutter present at the same time. Lee [12] has analyzed the noise performance of active and passive-weighted architectures and Holzman [13] has derived equations for the output TOI for

TABLE I
RECEIVE PERFORMANCE PARAMETERS FOR ACTIVE- AND PASSIVE-WEIGHTED PHASED ARRAYS NORMALIZED TO THOSE OF AN ARRAY WITH UNIFORM ILLUMINATION. M ELEMENTS; w_i IS THE VOLTAGE AMPLITUDE OF THE ith ELEMENT; F_i IS THE NOISE FIGURE OF THE ith T/R MODULE (INCLUDING RADIATING ELEMENT); $F_{\min}$ IS THE NOISE FIGURE OF THE T/R MODULE OPERATING WITH MAXIMUM GAIN; I_0 IS THE T/R MODULE OUTPUT THIRD-ORDER INTERCEPT (TOI) FOR MAXIMUM GAIN; $I_{i,0}$ IS THE OUTPUT TOI OF THE ith T/R MODULE; ε TAPER IS THE APERTURE EFFICIENCY [11]

Parameter	Active Weighted Array	Passive Weighted Array
Signal Gain	$G_s = (\sum_{i=1}^{M} w_i)^2 / M^2$	$G_s = \varepsilon_{taper}$
Noise Gain	$G_n = \sum_{i=1}^{M} \lvert w_i \rvert^2 / M$	$G_n = 1$
Input Noise Figure	$F_{in} = \sum_{i=1}^{M} w_i^2 F_i / (F_{min} \sum_{i=1}^{M} w_i^2)$	$F_{in} = 1$
Output TOI	$I_o = (\sum_{i=1}^{M} w_i)^3 / M^2 I_0 (\sum_{i=1}^{M} w_i^3 / I_{i,0})$	$I_o = \varepsilon_{taper}$

both array architectures. Table I summarizes their equations for beamformer signal gain, noise gain, input noise figure, and output TOI for both phased-array architectures [11]. Signal gain includes all passive combining gain and active T/R module gain plus any losses in the beamformer. The noise gain excludes the gain of the combiners. The input noise figure is the noise figure referenced to the input of the T/R module and the output TOI is referenced to the output of the sum channel. The equations are normalized to the performance of a uniformly illuminated array, i.e., an array with uniform combiners and all T/R modules with maximum receive gain.

If we assume that reactive combiners are used in the passive-weighted array, the noise gain and input noise figure will be the same as those of the uniform array. The TOI and signal gain are reduced by the taper efficiency, typically 1–2 dB. The T/R modules are operated at maximum gain, so no reduction in noise gain occurs. On the other hand, for active-weighted array, the T/R module gain varies with position in the array. For tapered aperture illuminations, the signal and noise gains of the active-weighted architecture can easily be 6–8 dB less than those of the passive-weighted array. The noise figures of the two arrays are not much different, since the T/R module's weighting is set by a VGA or attenuator at the back of the module's receive chain. For a module at the array edge where the attenuation is severe, the module noise figure is higher; however, that module's contribution to the system noise figure is small because its noise figure is multiplied by the square of its voltage weight. The effect of the active-weighted array's lower gain can be significant in a radar system when we consider the stages that follow the phased array. For instance, if a receiver follows the antenna, the contribution of its noise figure is reduced by the noise gain of the antenna, viz.,

$$F_{\text{system}} = F_{in,a} + (F_{\text{receiver}} - 1)/G_{n,a}$$

where all quantities are referenced at the input. This equation applies to both array architectures. The passive weighted antenna will have the lower overall system noise figure because its noise gain is not reduced by the amplitude taper.

TABLE II
RECEIVE PERFORMANCE PARAMETERS FOR ACTIVE- AND PASSIVE-WEIGHTED PHASED ARRAYS NORMALIZED TO THOSE OF AN ARRAY WITH UNIFORM ILLUMIANTION. 16 384 ELEMENTS, −40 dB ILLUMINATION [11]

Parameter	Active Weighted Array	Passive Weighted Array
Signal Gain	-9.7 dB	-2.2 dB
Noise Gain	-7.5 dB	0 dB
Input Noise Figure	5 dB	5 dB
Output TOI	-9.7 dB to -5.4 dB	-2.2 dB

As a vehicle to compare the two architectures, we use a rectangular array of 16 384 elements arranged on a triangular lattice with 256 rows and 256 columns [11]. If we apply a linear–linear −40-dB Taylor taper to the array, we obtain an aperture efficiency of −2.2 dB. Table II compares the resulting active and passive-weighted performance.

We see that the passive-weighted array has 7.5 dB more signal and noise gain than the active architecture. If the passive array has 15-dB noise gain and a 5-dB input noise figure and is followed by a receiver with a 5-dB input noise figure, the system noise figure is 5.09 dB. An active antenna with the same T/R module would have only 7.5-dB total noise gain and a system noise figure of 5.50 dB.

The choice of providing amplitude taper in the beamformers or the T/R modules will depend on the required system noise performance, beamformer complexity, and cost. The additional beamformer required for the passive-weighted array will impact array packaging as it requires additional volume and will increase array cost (<10%).

V. BEAMFORMER ARCHITECTURES FOR HIGH RELIABILITY

Since active phased-array antennas contain large number of active components, the antenna performance degrades gracefully as components fail over time. In addition to the T/R modules, the active phased arrays may contain large number of power supplies or dc to dc converters; each dc to dc converter feeds a group of T/R modules. A block diagram of the antenna with these active components is shown in Fig. 8. In Fig. 8, a group of T/R modules share a common control module that houses voltage regulators, drain switches, digital controls, and memory chips. A distributed power system is generally chosen to increase system clutter improvement factor (CIF) [14] and reliability [15]. The choice of beamformer architecture and packaging of components will affect the system reliability. Consequently, the design of active phased arrays often involves a tradeoff between production cost, life-cycle cost, and performance.

Strategies for designing active phased-array antenna architecture with high reliability are discussed in this section. It is shown how to consider fault tolerance in the design of the antenna architecture, so that replacement of failed components can be avoided for an extended period of time. The reliability of an antenna is described by its mean-time-between-failures (MTBF)—failures that cause the antenna performance to fall below the acceptable level. We discuss the design of active phased-array architectures for maximizing antenna MTBF. The antenna MTBF is generally defined in terms of a specified degradation in receive peak and/or rms sidelobes from the

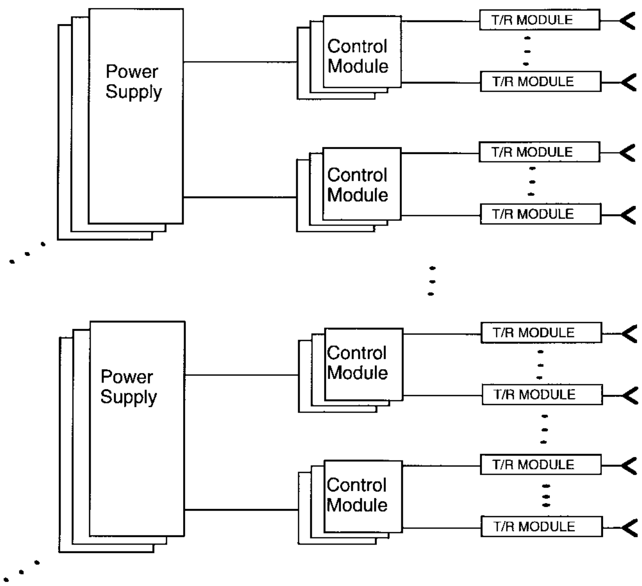

Fig. 8. Reliability block diagram of the antenna.

nominal level [15]. For a phased array that is deployed in the field for a length of time, it is desirable to have the antenna MTBF exceed the deployment time, so that the failed components can be replaced at the depot and the need for spare parts in the field is minimized.

As antenna components fail randomly, the sidelobe performance degrades. If the components fail randomly in single clusters, a fairly large number of components can be allowed to fail before the antenna sidelobe performance falls below a specified value. However, if the components fail in large clusters, the number of allowed failures for a given sidelobe degradation is much smaller. Therefore, the antenna architectures which minimize failure of big clusters of elements will increase the antenna MTBF.

Based on this definition, we can calculate the MTBF of a large active phased-array antenna given the types of components, their quantities, and their MTBF's. In addition, we must know the antenna performance degradation per failure for each component-type and the antenna's minimum acceptable level of performance. Consider peak sidelobe level. Table III shows the number of element failures allowed for clusters of one, two, four, and eight for the peak sidelobe level increase of 3 and 6 dB for an 8000-element circular array with a 40-dB Taylor sidelobe taper. The element lattice is triangular with about half-wavelength spacing.

The data in Table III was obtained by calculating the antenna patterns for an aperture with different size clusters of failed elements removed in a random fashion. The peak sidelobe degradation was determined for many different trials for each cluster size and the numbers shown in Table III represent the average. These simulations were done for a large array size (about 8000 elements). The results in Table III could be used for other arrays of comparable size or larger. As the size of the array is increased, the fractions in Table III will increase and as the size of the array is decreased, the fractions in Table III will decrease toward zero. Note that the data in Table III is independent of frequency.

TABLE III
ALLOWED FRACTIONS OF ELEMENT FAILURES FOR 3- AND 6-dB INCREASE IN THE PEAK SIDELOBE LEVEL AS A FUNCTION OF CLUSTER SIZE FOR AN 8000-ELEMENT CIRCULAR ARRAY WITH TAYLOR 40-dB AMPLITUDE TAPER AND TRIANGULAR LATTICE, HALF-WAVELENGTH ELEMENT SPACING. ELEMENTS ARE ADJACENT AND WITHIN THE SAME COLUMN

Cluster size	Failures for 3 dB SLL increase	Failures for 6 dB SLL increase
1	3.2%	6.5%
2	1.8%	4.1%
4	1.0%	2.6%
8	0.55%	1.1%

TABLE IV
CALCULATION OF ANTENNA MTBF FOR A 3-dB RISE IN PEAK SIDELOBES FOR AN 8000-ELEMENT ARRAY

Component	quantity	MTBF (Khrs)	Failure rate (hr^{-1})	Component failures allowed	Contribution to MTBF (hrs)	Cumulative Antenna MTBF (hrs)
T/R Module	8,000	200	0.04	256	6,400	6,400
Control Mod	1,000	100	0.01	5	500	464
Power supply	1,000	50	0.02	5	250	**162**

We have curve fit the data in Table III to develop a single equation describing sidelobe level increase as a function of array size. We assume that the number of failures is proportional to array size for a given cluster size. As the array size decreases, a particular cluster failure causes more sidelobe level increase in proportion to its area. The sidelobe level (SLL) increase in dB as a function of cluster size, array radius, and frequency is given by the following equation:

$$\text{SLL Increase} \cong 0.0885S/(FR) + 6.516(S/FR)^2$$

where S is the element cluster size, F is the frequency in Ghz, and R is the radius of the array in feet.

For example, consider the 8000-element array. Twelve two-element cluster failures causes 0.46-dB sidelobe level increase. If we lose three four-element clusters of elements, we also get approximately 0.46 dB increase in sidelobe level. Now, halve the array radius so the array size reduces to 2000 elements. For this smaller array, three two-element clusters failure also causes approximately 0.46-dB sidelobe increase. As the SLL increases, we would expect failures to have less and less impact.

In this section, we provide guidelines for selecting an active array architecture that maximizes the antenna MTBF. We begin with the phased-array antenna architecture in Fig. 8 and assume that each control module and each power supply drives eight T/R modules. From the maximum allowable number of failures given in Table III for an 8000 element array, we can calculate the antenna MTBF as shown in Table IV for a 3-dB rise in peak sidelobes.

The antenna MTBF calculation in Table IV shows antenna MTBF due to failures of single component types and cumulative antenna MTBF. The antenna MTBF due to single component is obtained by multiplying the failure rate by the number of element failures allowed. From the third row, we see that the MTBF of the antenna is only 162 h, i.e., the antenna must be shut down approximately once a week for repair of failed components. Clearly, if we only considered T/R modules, the antenna MTBF would be 6400 h, so the T/R module cluster size and MTBF are acceptable. However, the

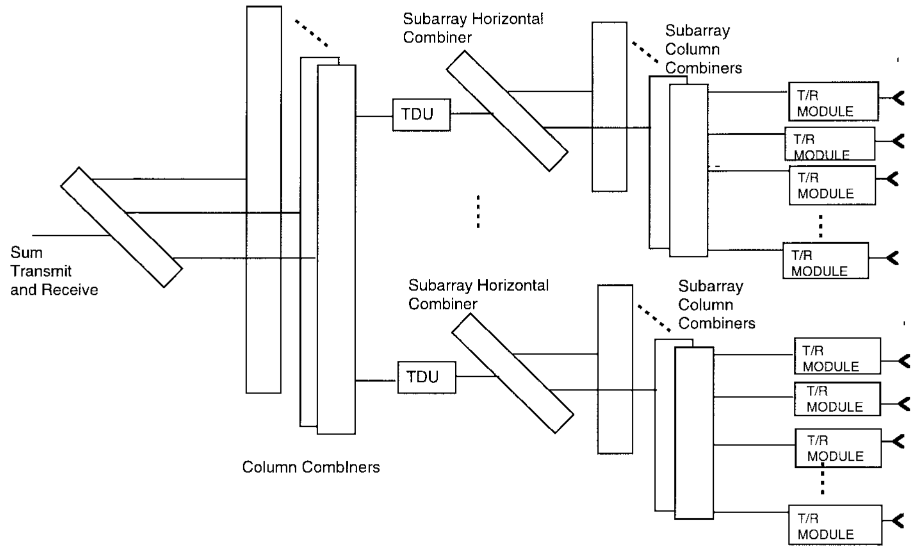

Fig. 9. Active-weighted beamformer architecture with subarrays for time-delay steering.

TABLE V
NO CLUSTER DESIGN. CALCULATION OF ANTENNA MTBF FOR A 3-dB RISE IN PEAK

Component	quantity	MTBF (Khrs)	Failure rate (hr^{-1})	Component failures allowed	Contribution to MTBF (hrs)	Cumulative Antenna MTBF (hrs)
T/R Module	8,000	200	0.04	256	6,400	6,400
Control Mod	8,000	280	0.0286	256	8,960	3,733
Power supply	8,000	50	0.16	256	1,600	**1,120**

MTBF due to the power supplies alone is only 250 h, and for the control modules it is only 500 h; these two components are determining the antenna MTBF.

We can raise the antenna MTBF if: 1) the MTBF of the individual components is increased; 2) the elements are driven in smaller clusters; 3) we use redundancy in the design; or 4) we raise the maximum allowable level of acceptable sidelobe increase. The best MTBF we can achieve using smaller clusters occurs when each element is driven by a single T/R module, control module, and power supply. Table V shows these calculations. We have increased the antenna MTBF to 1120 h. However, this improvement has come at a high cost since we have had to increase the number of components in the antenna by a factor of two and a half. Therefore, the selection of antenna architecture and cluster size will depend on the tradeoff between antenna cost and MTBF.

Another way to increase the MTBF is to provide redundancy in some components. From Table V, we note that the antenna MTBF is significantly reduced by the power supplies. Therefore, the antenna MTBF can be significantly improved by providing redundancy in the power supplies. This can be achieved by combining power supplies and feeding larger clusters of T/R modules. The redundancy in power supplies can be provided by an additional power supply in the paralleled group.

From the above discussion we note that the antenna manufacturing cost increases the antenna MTBF is increased. To increase the antenna MTBF, we had to increase the number of components to minimize the number of large element cluster failures due a single component failure. The life cycle cost of the antenna includes initial manufacturing cost and cost of repairing or replacing failed elements in the field. If the antenna MTBF is greater than the deployment period, the requirement for maintenance personnel can be minimized.

VI. BEAMFORMER NETWORKS FOR WIDE-BAND ACTIVE PHASED-ARRAY ANTENNAS

An array that is steered by phase shift, rather than time delay, will scan as frequency is changed. The instantaneous bandwidth of a phased-array antenna can be increased by dividing the aperture into subarrays and placing a time-delay network behind each subarray. The size of the subarray determines the instantaneous bandwidth of the antenna. Bandwidth criteria for phased-array antennas in terms of loss of antenna gain and relative amplitude of grating lobes have been developed for both narrow-band signal with frequency agility and for instantaneous wide-band signals [16]. In this section, we present beamformer architectures for instantaneous wide bandwidth active phased arrays.

Fig. 9 shows a typical wide-band beamformer architecture where the array is divided into subarrays with a time-delay-unit (TDU) steering each subarray. The TDU provides true time delay for each subarray and the T/R modules provide phase compensation for the quantized time steering. The size of the subarray determines the instantaneous bandwidth of the array. A rule of thumb for the bandwidth of the array was established in [16] as

$$\text{Bandwidth } (\%) = \text{Beamwidth (deg.)} \quad \text{(for CW signals)}$$
$$\text{Bandwidth } (\%) = 2 \text{ Beamwidths (deg.)} \quad \text{(for Pulsed signals)}.$$

The beamwidth in the above equations represents the beamwidth of the subarray in degrees.

The amplitude taper in the architecture of Fig. 9 is provided in the T/R modules, so all the combiners are uniform and, thus, all the subarrays are identical. In Fig. 9, for a subarray of $M \times N$ elements, elements in vertical columns are combined using $M \times 1$ vertical combiners and the outputs of the N-vertical combiners is combined with an $N \times 1$ horizontal

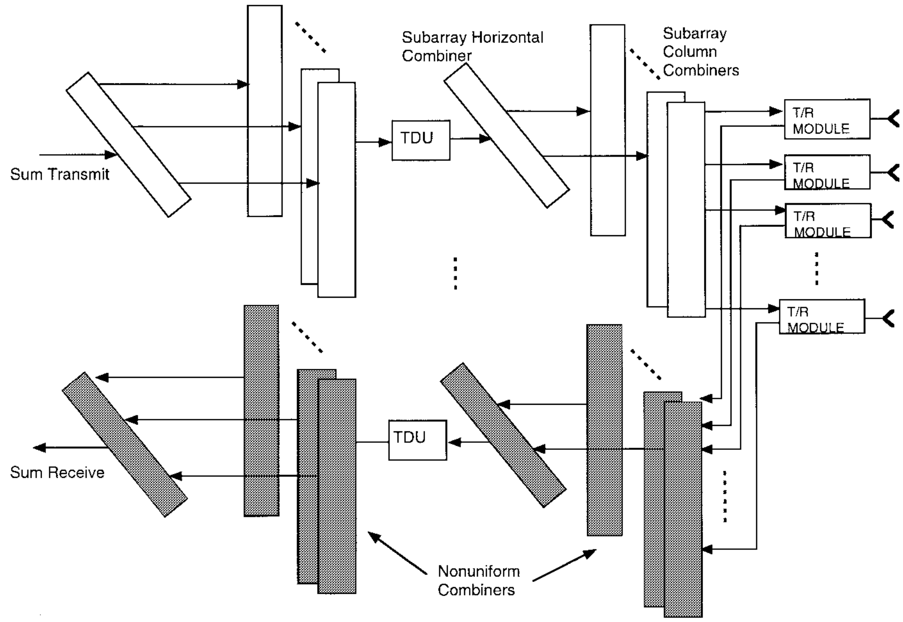

Fig. 10. Passive-weighted beamformer architecture with subarrays for time-delay steering.

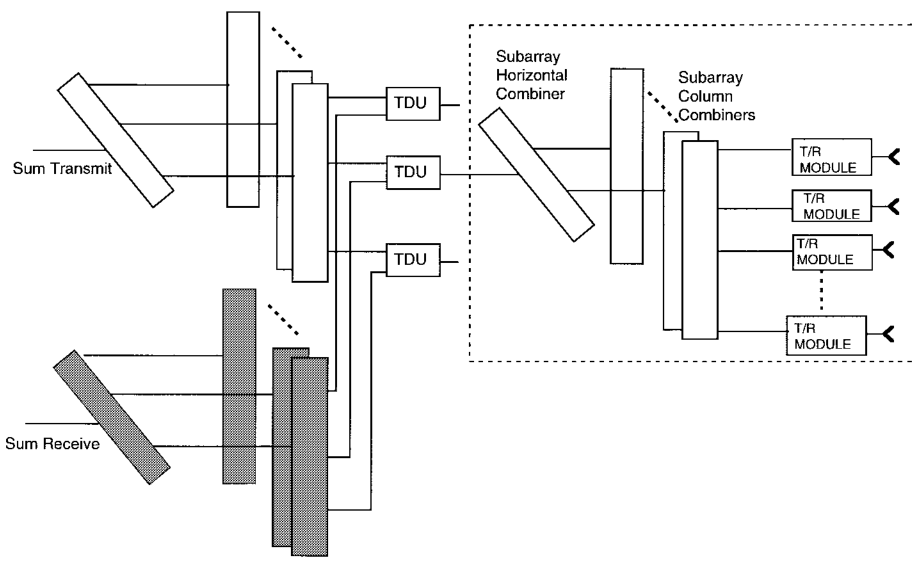

Fig. 11. Hybrid-weighted beamformer architecture with active-weighted subarray columns.

combiner to form the subarray input/output. The TDU provides the common time delay to all the elements in the subarray. The outputs of the TDU's are further combined using vertical and horizontal combiners to provide transmit input and receive output of the antenna. All the beamformers in Fig. 9 are uniform and all TDU's are identical. For large phased arrays, which may have hundreds of subarrays, one common set of parts is very desirable from the producibility and maintainability prospective.

Fig. 10 shows a wide-band passive-weighted array architecture. We need two beamformers, one for transmit and one for receive. Further, we must use two sets of TDU's or diplex the transmit and receive signals through a single set; either option is more complex than the active-weighted architecture. In addition, the receive beamformer requires nonuniform combiners so that each subarray has unique set of components. For an antenna with quadrantal symmetry, the number of unique subarrays can be reduced by a factor of four.

Figs. 9 and 10 show beamformer architectures for the sum beam only. This architecture can be extended to three monopulse beams by providing a TDU in each of the monopulse beams.

As discussed in Section IV, the active weighted architecture has lower noise performance than the passive-weighted architecture. As a compromise between the more complex passive-weighted architecture and lower performance active-weighted architecture, we can combine the characteristics of both in a hybrid architecture shown in Fig. 11. For a beamformer with multiple levels of combining, some combiners can be uniform, while others can be nonuniform. In that way, we can reduce the number of unique nonuniform combiners in the antenna and have higher performance [11]. In Fig. 11, the vertical combiners and the horizontal combiner in the subarray are uniform weighted and common to both transmit and receive paths. Partial amplitude weighting can be applied in the modules in the receive mode. For a large phased array, by making the first-level vertical combiners in the subarray uniform, we have reduced the number of nonuniform combiners with performance still significantly better than the active-weighted architecture.

VII. Conclusion

Active phased-array antennas provide significant improvement in performance over their predecessor passive phased-array antennas. In addition to the reduction in transmit and receive losses, active arrays can provide wide instantaneous bandwidth and high average radiated power. Active phased arrays offer many choices for beamformer architectures. This paper has examined the beamformer architectures for active phased-array radar antennas for narrow and wide bandwidth and for high reliability. The passive-weighted and active-weighted architectures were compared for beamformer complexity and antenna noise performance. The material presented in this paper should provide sufficient information for an antenna design team to choose an optimum beamformer architecture for a given set of requirements.

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