1

AESA Overview

1.1 Introduction

The past 30 years have seen a significant increase in the capability of active electronically scanned arrays (AESAs). What was once deemed a relatively new and expensive technology has now proliferated in many applications such as defense, communications, and the automotive industry. The advancement of microelectronics and receiver technology has also benefited AESAs. The ability to produce microelectronic circuits and high-speed wide bandwidth receivers in a small form factor has made AESAs a realizable commodity for array applications. Additionally, and arguably most crucial, is the ability to produce AESAs cost effectively. In their infancy stage, AESAs were deemed cost prohibitive for any application outside of the defense industry (specifically airborne radar). This, however, is no longer the case. As an example, the automotive industry uses small inexpensive AESA radars for collision avoidance (Tokoro et al., 2003).

1.2 AESA History

Although AESAs are becoming more widespread, many people unfamiliar with AESAs believe it is a new technology. However, AESAs were being developed as far back as the early 1960s. The driving application was radar where agile and simultaneous beams are highly advantageous for tracking fast-moving targets. In 1960, Bell Labs proposed a phased array to replace the Nike Zeus radar (Figure 1.1) (Labs, 1975). This radar used a distributed phased array approach employing multiple reflector antennas that were spaced apart. Each reflector antenna had its own transmitter and receiver. This enabled simultaneous beams accomplishing detection and tracking at the same time. Key features of this radar were long distance detection, track generation, discrimination of warheads from decoys, and tracking of outbound interceptor missiles (Labs, 1975).

Active Electronically Scanned Arrays: Fundamentals and Applications, First Edition. Arik D. Brown.

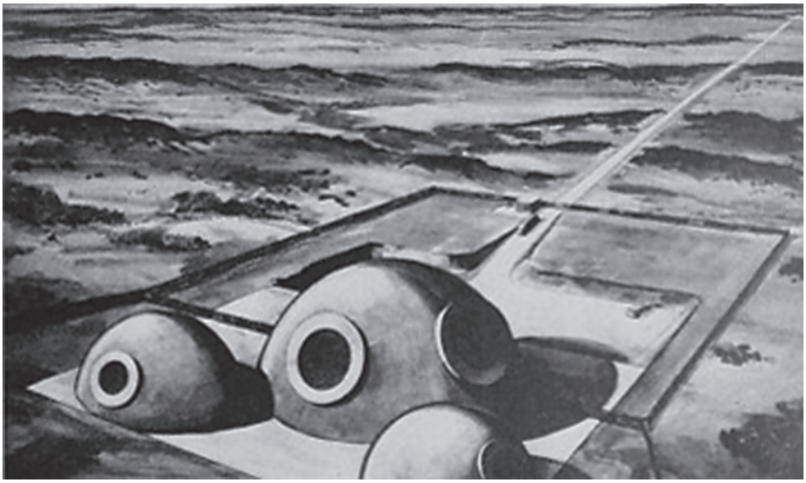

Figure 1.1 Zeus Multi-Function Array Radar, developed by Bell Labs, utilized a distributed phased array. (Labs, 1975)

In the early 1970s, airborne radar became the driver for AESA development. AESAs opened up new possibilities to provide superior air dominance. Agile beams that could be scanned rapidly on the order of microseconds with no moving parts (gimbal), higher reliability (MTBF) and graceful degradation in performance were some of the key features that caused a flurry of development to build high-performance airborne AESA radars. Over time this led to the development of AESAs that supported multi-function capability such as search, track while scan, synthetic aperture radar, and precision geolocation.

The 1980s and 1990s saw the expansion of AESAs from air to maritime and land. The increase in the repeatability of microelectronic circuits and the decrease in the cost of development made AESAs tenable for large arrays that could be used for maritime- and land-based radar systems. An airborne radar is limited in how big it can be for fighter applications and to some extent for long-range surveillance, but maritime and land radars do not have the same power and weight limitations. In order for a very large AESA to be built (e.g., > 10s of square meters), cost cannot be prohibitive.

In the 2000s there was an increase in the development of AESAs for Ka Band. AESAs at these frequencies can leverage semiconductor wafer processing providing a dramatic decrease in cost. AESAs at these frequencies can support a large number of elements (>> 1,000) and also enable the ability to use wider bandwidths due to the increase in frequency. As an example, for an AESA built for X band, a 22 percent bandwidth represents $\sim 2\,\text{GHz}$ of operational bandwidth;

however, at Ka band a 22 percent bandwidth represents ~ 8 GHz of operational bandwidth. For applications such as communications, this is very attractive due to the increased spectrum for the same percent bandwidth. In addition to communications, the automotive industry has leveraged AESAs at Ka band frequencies for radars that support automotive collision prevention.

From approximately 2010 until the present, we are now seeing a growing increase in the use of AESAs by smaller-sized companies that are able to build more affordable AESAs for radar applications such as active protection systems (APS), counter unmanned aerial systems (C-UAS), counter rockets artillery and mortars (C-RAM) and short-range air defense (SHORAD). Examples of this are the enhanced compact hemispheric radar (eCHR) and improved and enhanced multi-mission hemispheric radar (ieMHR) (Figure 1.2) built by RADA. These 4D AESA radars have an excellent performance-to-price ratio, are software defined, and support multi-mission operation.

Currently AESAs are also extending beyond radar into applications such as electronic attack (EA), signals intelligence (SIGINT), and electronic support measures (ESM). These capabilities existed in airborne AESA radars; however, they were adjunct capabilities to the primary radar function. We're now seeing AESA systems that are are specifically designed for the applications previously mentioned. As an example, the use of AESAs for EA on the mid-band pods for the E-18G Growler (Reim, 2021) shown in Figure 1.3, in addition to InTop (Grumman, 2019), show how the use of AESAs has expanded beyond solely radar.

1.3 AESA Applications

As previously mentioned, the original force and impetus behind AESA development and application was radar. AESA technology advancements, especially in the area of airborne radar, created a technology base that could be used for other applications. The features and characteristics that make AESAs attractive for radar have a similar attraction for other technology areas. The applicability of AESAs for these areas is described next.

1.3.1 RADAR

Initial radars used mechanically scanned arrays (MSAs). MSAs use a mechanical gimbal to point a reflector antenna. An example is illustrated in Figure 1.4 that shows the MSA for the APG-78. An advantage of MSAs is that they do not suffer scan loss. (Scan loss will be explained in Chapter 3.) However, the speed with which the array beam can be scanned spatially is limited by the gimbal. AESAs

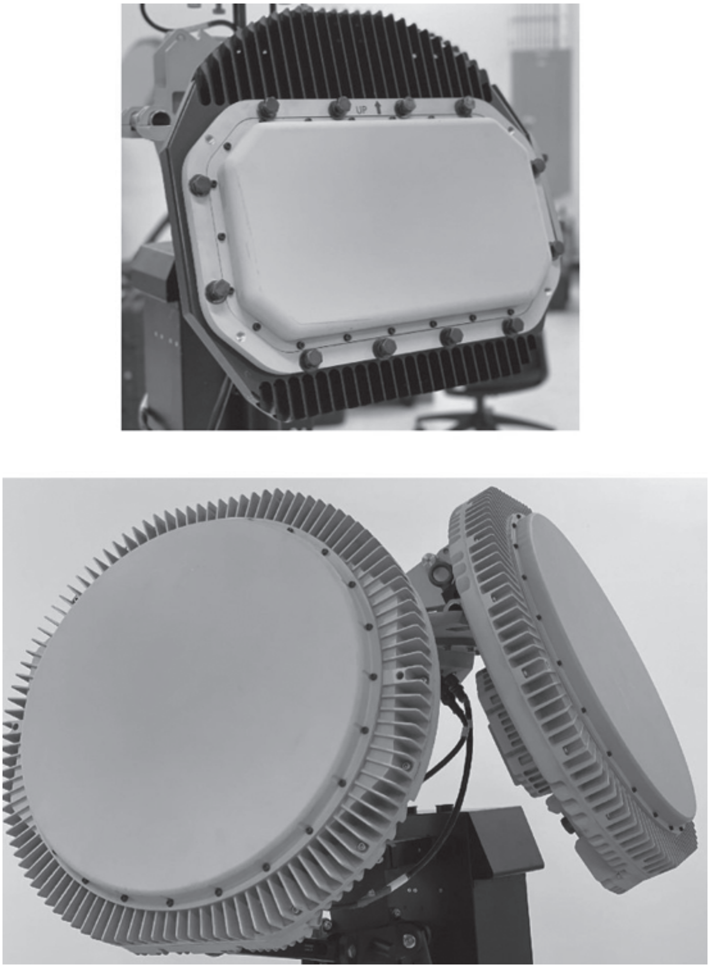

Figure 1.2 RADA's eCHR (top image) and ieMHR (bottom image) utilize AESAs to provide multi-mission capability.

enabled a substantial increase in scan volume speed on the order of milliseconds to microseconds. Current AESAs can scan beams on the order of nanoseconds. Figure 1.5 shows the difference in how beam scanning is accomplished between an MSA and an AESA. The AESA has phase shifter devices that apply a different phase at each array element. This causes the array beam to coherently add at any commanded scan angle, which is called beam scanning (Figure 1.5). The theory behind this will be covered in Chapter 2, and the details of a transmit receive module (TRM) will be explained in Chapter 4. TRMs contain the phase shifter devices that enable beam scanning. Since this scanning is done electronically, it is

Figure 1.3 The US Navy is employing AESA technology on the Next Generation Jammer mid-band pods for the EA-18G Growler. (US Navy photo by Erik Hildebrandt)

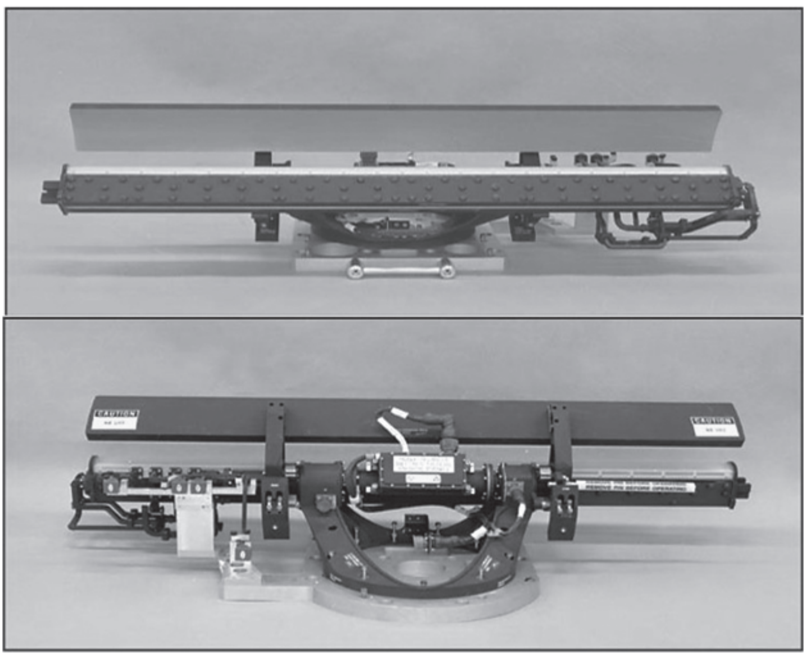

Figure 1.4 The APG-78 is an example of an early radar that used an MSA. Although effective, it does not have the beam agility of an AESA.

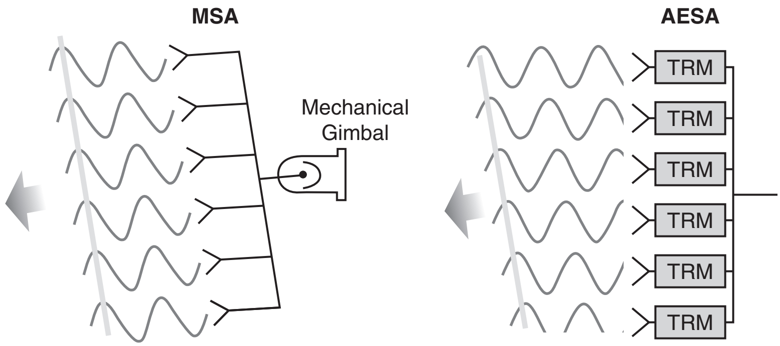

Figure 1.5 AESAs are able to electronically scan the array beam as opposed to mechanical scanning by MSAs. This provides orders of magnitude improvement in spatial scanning ability.

inherently faster than the mechanical instantiation of beam scanning by the MSA. This is commonly called *beam agility*.

The transition from MSAs to AESAs for radar was not a direct leap. A transitory architecture was developed that is called a passive electronically scanned array (PESA). This architecture is shown in Figure 1.6. The only electronics in the front-end array are phase shifters, which, as described previously, apply a phase shift to each array element. Amplification of the signal prior to transmission and on reception of signals is done with a single high-power amplifier (HPA) and a low noise amplifier (LNA). This architecture inherently suffers from a large amount of loss on transmit and receive. When transmitting, losses after the HPA directly degrade the transmitted power, which for a radar affects range performance. On receive, the same phenomenon occurs, and the loss attenuates the incoming signal before amplification by the LNA.

AESAs overcame this limitation of PESAs by implementing HPAs and LNAs at each element in the array (in some cases groups of elements). This greatly minimizes the loss on transmit and receive and is a large advantage of AESAs over PESAs. A side-by-side comparison of the two architectures is shown in Figure 1.6. The challenge initially for AESAs was to make the microelectronic circuits that contain the HPAs, LNAs, phase shifters, TR switches, and other electronic devices repeatable and affordable. GaAs was an important breakthrough to enable these type of microelectronic devices to be built, thereby making AESAs viable for mission applications.

What is readily noticeable in the PESA architecture diagram is that if the transmitter or receiver fails, the entire array is inoperable. This is known as a *single point failure*. This is undesirable since if it occurs during the mission, the operator is unable to use the radar, and also the transmitter and/or receiver must be replaced. Both of these issues have a negative effect on reliability and specifically MTBF. This is a critical performance parameter especially for DoD applications.

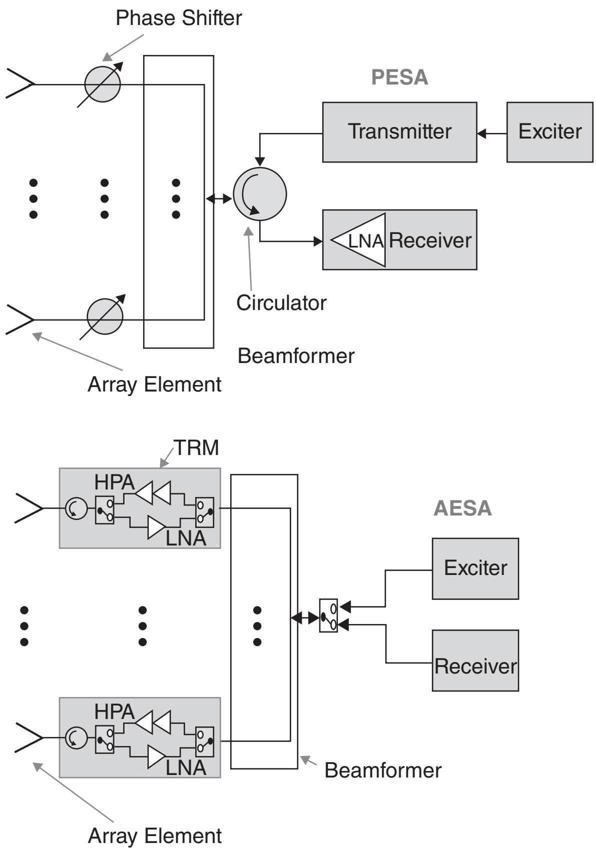

Figure 1.6 An AESA is a distributed architecture in contrast to a PESA. This provides advantages in increased radiated power and increased sensitivity on receive due to minimization of losses as compared to the centralized transmitter and receiver for the PESA.

Unlike PESAs, AESAs greatly improve MTBF. This is because if a single TRM fails, the array is still operational. In fact, depending on the size of the AESA (number of elements), as many as 6–10 percent of the elements could fail, and the array would still be operational and perform. This is commonly referred to as *graceful degradation*. This will be discussed in more detail in Chapter 2. Figures 1.7 and 1.8 show two examples of AESAs that exhibit graceful degradation.

1.3.2 Electronic Warfare

Airborne AESA radars have implemented EA and ESM modes for many years. However, the primary mode is typically radar related (search/surveillance,

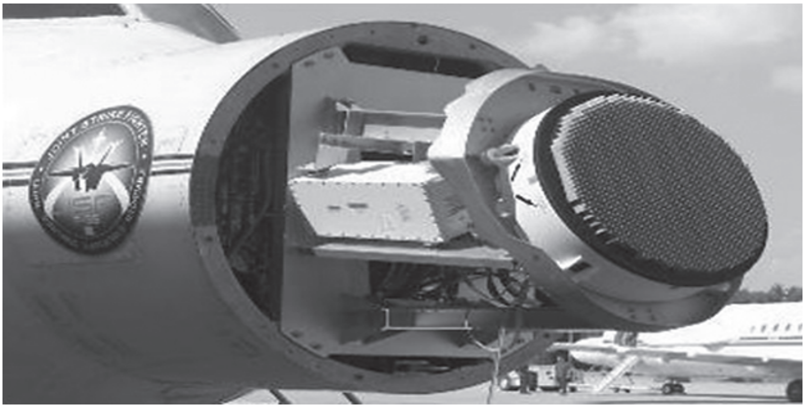

Figure 1.7 The APG-81 AESA demonstrates graceful degradation due to the large number of array elements.

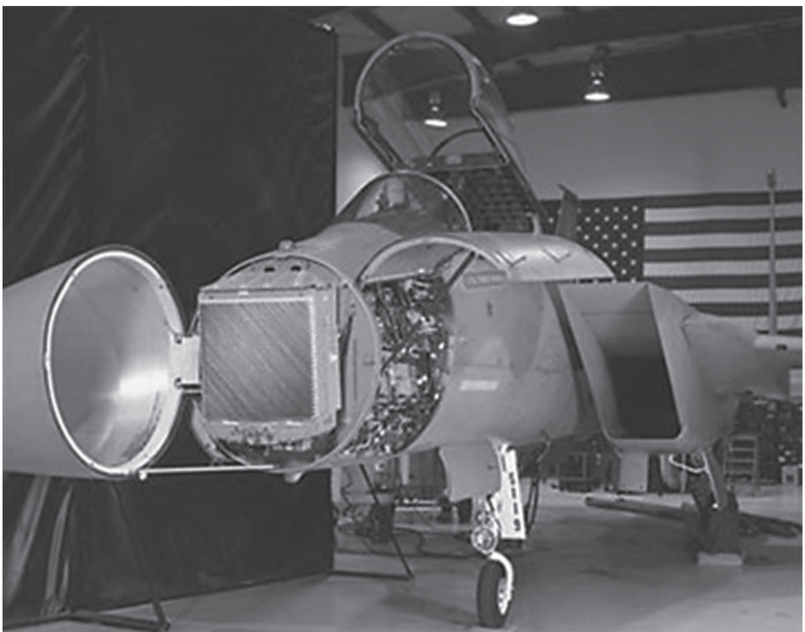

Figure 1.8 Similar to the APG-81, the APG-63 V2 AESA is another example of graceful degradation due to the large number of array elements. (Figure courtesy of Raytheon.)

tracking, SAR, etc.) while EA/ESM modes are ancillary. AESAs are now being used for EW functions only, which is a paradigm shift from years past. Examples of this are the Next Generation Jammer (Reim, 2021) and Integrated Topside (Grumman, 2019) programs for the Navy. Both are employing AESAs for EW use.

1.3.2.1 Electronic Attack

For EA, AESAs provide several key benefits to be used in an EA system. These benefits are described below:

- Directional high gain beams - Traditional EA systems use antennas that are omnidirectional or have very little gain. This means the effective radiated power (ERP), which is the product of the antenna gain and transmitted power, is primarily going to be driven by the available transmitted power since the antenna has a small amount of gain. AESAs are advantageous relative to ERP because they have large antenna gains and have the ability to transmit a large amount of power. This dramatically increases the standoff range for which the EA system can jam threats.
- Simultaneous beams - In typical EA engagements, there are multiple threats within the system's field of view (FOV) posing imminent danger to pilots flying in the vicinity. These threats can be spatially and frequency diverse. AESAs have the ability to be broken into subarrays allowing sections of the array to operate independently. Additionally, multiple beamformers can be implemented in the same AESA providing the ability to transmit beams at different frequencies by power sharing of the array. This makes AESAs optimal for defeating threats that are spatially and frequency diverse.
- Beam agility - Multiple threats can be jammed by either changing frequency for threats located in the same location or changing the frequency and location of the jamming beam for threats in different locations. The latter is commonly referred to as spatial commutation. Because AESAs have agile beams than can be scanned on the order of nanoseconds, they can be employed for spatial commutation.
- Wide instantaneous bandwidth (IBW) - Threats have evolved by employing wider bandwidth lower-power waveforms to search and detect. To counter this the jamming system has to be able to mimic these waveforms to reproduce and re-transmit for jamming. AESAs now have the capability to support large IBWs, which can be used in these situations.

1.3.2.2 Electronic Support Measures

Benefits for ESM are described below. The features an AESA provides for ESM are similar to EA, but the benefits are different because ESM employs passive reception of threat signals. AESAs that can support *both* EA and ESM are extremely powerful.

- High gain beams - Receive sensitivity is of utmost importance for ESM. It determines the smallest amplitude threat signal that can be detected for geolocation or other purposes. AESAs have high gain beams, which translates to superior sensitivity.
- Simultaneous beams - High gain beams have much smaller beamwidths than traditional omni-directional ESM antennas. This means the ability to search a given volume in space will take longer. To counter this, simultaneous beams provide the ability to search a spatial volume faster *and* with high sensitivity.
- Beam agility - Similar to simultaneous beams, beam agility enables the AESA to scan a spatial volume rapidly.
- Wide IBW - This also enables the ability to scan faster in the *frequency domain*. Being able to interrogate the frequency spectrum of interest rapidly is critical. AESAs can support this by using true time delay (discussed in Chapter 2).

1.3.3 Communications

With the expansion of many communication systems to Ka band and higher, AESAs are now highly attractive for communication applications. For low-frequency communications, AESAs are not a suitable choice since they would have to be extremely large and in most cases cost prohibitive. For higher frequencies, this barrier is removed, and AESAs can be used. The benefits for communications are described below.

- High gain beams - Similar to EA, high gain beams increase the range of communication systems. However, of perhaps even greater importance is that high gain beams increase SNR, which allows the use of more complex waveforms for increased data transmission rate.
- Simultaneous beams - This feature of AESAs allows a single system to reach multiple users at the same time. This is highly valuable for creating a persistent and reliable communications system.
- Beam agility - The beam agility of AESAs enables them to service users in diverse spatial locations. This eliminates the need of using multiple antennas to cover different regions spatially.
- Wide IBW - Wider bandwidths enables increased data throughput. It also supports more efficient use of the transmission frequency spectrum for waveforms such as OFDM. AESAs enable the ability to transmit and receive high gain, and simultaneous, agile beams with a wide IBW.

1.3.4 Signals Intelligence

SIGINT can be thought of as requiring only an ESM system. This means that the SIGINT AESA does not transmit and only receives signals from the environment.

Its sole purpose is to find small and large signals[1] across frequency with the ability to geolocate the signals and/or demodulate them for intelligence. The AESA benefits described for ESM are directly applicable for SIGINT. An interesting point to highlight is that since SIGINT AESAs do not transmit, they then have more space for additional receive electronics. This opens up the design space for increasing the number of beams in the AESA, making it even more powerful for rapidly scanning in both the spatial and frequency domains.

1.4 AESA Point of Reference

Before introducing the AESA block diagram, it is necessary to first review the relation between received and transmitted power from an array/antenna. This relation can be described with an equation that is extensively used in radar that is called the radar range equation (RRE), which is based upon the Friis transmission equation (Balanis, 1982). This equation represents the signal power that is transmitted, reflected from a target, and received by the same or another antenna, and the ratio of that power to the noise produced in the environment and by the system electronics, which is called the signal-to-noise ratio (SNR) (Balanis, 1982) and (Skolnik, 1990). For transmit-only and receive-only applications, this equation is still applicable and can be used by omitting certain parameters, which will be discussed in the following paragraphs. AESAs are a major contributor to the RRE for both the signal power and the noise power, so understanding the RRE is important for AESAs. The driving requirements flowed to an AESA are based upon system-level performance parameters that affect the RRE.

The RRE will first be described in the context of a radar, and later it will be pointed out how it applies for other non-radar applications. First, the signal power in the RRE will be addressed. Consider an antenna with a transmit gain G_{TX} and power P_{TX}. The product of P_{TX} and G_{TX} is the effective radiated power and represents the amount of power radiated in the far-field. The far-field region is a prescribed distance away from an antenna where the field intensity is essentially independent of the distance from the antenna (Balanis, 1982). This distance is calculated using the equation $R = \frac{2\,D^2}{\lambda}$, where R is the distance from the antenna, D is the maximum overall length of the antenna, and λ is the RF wavelength at the radiated frequency ($\lambda = \frac{c}{f}$, where c is the speed of light and f is the RF radiated frequency) (Balanis, 1982). In general, G_{TX} is a function of angle (θ, ϕ); however, for the purposes here it is assumed that G_{TX} represents the peak of the antenna gain

1 This is referred to as dynamic range and is calculated for an AESA in Chapter 6.

pattern. The radiated power decreases proportionally by the distance or range (R). The radiated power can then be represented as:

$$\frac{P_{TX}G_{TX}}{4\pi R^2} \left[\frac{\mathrm{W}}{\mathrm{m}^2}\right]. \tag{1.1}$$

The radiated power in Equation 1.1 is then incident upon an object or target, which reflects and effectively reradiates this energy. The parameter that describes this is the radar cross section, σ [m^2], and represents the amount of energy that is reflected back in the direction of the radiating antenna. Similar to the original radiated power the reflected power, decreases proportional to R. The power that arrives back at the radiating antenna can be represented by:

$$\frac{P_{TX}G_{TX}\sigma}{(4\pi)^2 R^4} \left[\frac{\mathrm{W}}{\mathrm{m}^2}\right]. \tag{1.2}$$

The last step in computing the total reflected power at the transmitting antenna is to multiply the power in Equation 1.2 by the area of the antenna. The total received power is shown in Equation 1.3 and will be referred to as S. It will be shown that this S is the signal power for the SNR.

$$S = \frac{P_{TX}G_{TX}\sigma A}{(4\pi)^2 R^4} \ [\mathrm{W}] \tag{1.3}$$

The A in Equation 1.3 is the effective capture area of the antenna and does not represent the actual physical dimension of the array. This equation form of S is the most generic in that it can be applied to both monostatic (transmitting and receiving antennas are the same) and bistatic (transmitting and receiving antennas are different and spatially separated) radars. For the the purposes of this discussion it is assumed monostatic. With this assumption, Equation 1.3 can modified by using the familiar expression of $G = \frac{4\pi A}{\lambda^2}$. Equation 1.3 can then be written as:

$$S = \frac{P_{TX}G_{TX}^2\sigma\lambda^2}{(4\pi)^3 R^4} \ [\mathrm{W}]. \tag{1.4}$$

In Equation 1.4, it is seen that in order to maximize the signal power S for a given R, P_{TX} and G_{TX} must be maximized as well. As discussed earlier, AESAs inherently have high gain and are capable of transmitting large amounts of power. This is how the AESA directly affects and improves S. As an example, the effect of an MSA on S is calculated using the same expression in Equation 1.4. The difference is that reflector antennas are much less efficient than an AESA and have losses on the order of 60%. AESAs typically have losses on the order of 90%, which directly maximizes S in comparison to an MSA. Additionally, as was shown in Figure 1.6, the losses after the transmitter in an MSA are reduced with an AESA due to the AESA's distributed HPA architecture. This directly affects P_{TX} and thereby S.

To complete the SNR equation, the noise power N that competes with S must be calculated. The expression for N is shown in Equation 1.5. k [W/Hz*K] is

Boltzmann's constant, T_o [K] is the noise temperature, B [Hz] is the noise bandwidth, and F is the noise factor, which represents the noise added by the system to the incoming noise from the environment (Pettai, 1984).

$$N = kT_oBF \text{ [W]}. \tag{1.5}$$

In an AESA, the LNAs are placed close to the array elements minimizing the added loss and therefore minimizing F. This decreases the amount of noise that is seen by the receiver and competes with S. The equation for SNR can then be written as:

$$SNR = \frac{S}{N} = \frac{\frac{P_{TX}G_{TX}^2\sigma\lambda^2}{(4\pi)^3R^4}}{kT_oBF}, \tag{1.6}$$

which can be simplified as:

$$SNR = \frac{P_{TX}G_{TX}^2\sigma\lambda^2}{(4\pi)^3R^4kT_oBF}. \tag{1.7}$$

From a design perspective, Equation 1.7 highlights the performance parameters that are affected by the AESA. These parameters are P_{TX}, G_{TX}, and F. For an optimal AESA design, the transmit power, array gain, and noise figure must be optimized and balanced to achieve a high-performance, cost-effective solution.

Thus far, the RRE equation has been discussed from a radar perspective of transmitting and receiving energy for system operation. Next, the modifications to the RRE will be discussed for application to EA and ESM. For EA, the AESA is used to transmit as much power as required to jam the target of interest. Because of this, the receive noise power is not a driver, and the primary consideration is the signal power, S, as previously shown in Equation 1.4. A modification has to be applied to S because for jamming there is only a one-way loss from the AESA to the target, and there is no radar cross section to be concerned with. Taking these factors into consideration, Equation 1.4 then becomes:

$$S_{EA} = \frac{P_{TX}G_{TX}}{(4\pi)R^2} \cdot A_{threat} \text{ [W]}. \tag{1.8}$$

As previously discussed, P_{TX} and G_{TX} are maximized to deliver as much power as possible and are key drivers for the AESA design. Also, unlike in the radar case, the signal power for EA only has to overcome an R^2 loss. Lastly, A_{threat}, is the effective area of the threat antenna and is not a parameter that is affected by the AESA.

For ESM, a modification to Equation 1.7, has to be done for both the signal power, S, and the noise power, N. In an ESM system, the AESA operates in a receive-only mode. For this case, there is no transmit power from the AESA, and the power received is from the threat or signal of interest. Also, similar to the EA case previously described there is only an R^2 loss to be considered from the signal of interest to the AESA. Equation 1.7 can then be modified as:

$$SNR_{ESM} = \frac{(P_{TX}G_{TX})_{threat}}{4\pi R^2} \cdot \frac{A_{AESA}}{kT_oBF}. \tag{1.9}$$

This can be further simplified using the familiar relation $A = \frac{\lambda^2 \cdot G}{4\pi}$:

$$SNR_{ESM} = (P_{TX}G_{TX})_{threat} \cdot \left(\frac{\lambda}{4\pi R}\right)^2 \cdot \frac{1}{kB} \cdot \frac{G}{T}. \tag{1.10}$$

From Equation 1.10, a key performance parameter is shown in the form of $\frac{G}{T}$, where T is equal to T_oF. $\frac{G}{T}$ is commonly referred to as *sensitivity* and directly affects how well the ESM system can detect signals in the presence of noise. A sensitivity requirement is typically flowed down to the AESA and drives AESA performance. A sensitivity requirement is also flowed down for radar and communication AESA systems. Figure 1.9 provides a graphical illustration of the AESA performance parameters that affect performance for radar, EA, and ESM. Communications, although not pictured, can be represented as a combination of EA and ESM in terms of functionality. From the AESA's perspective, the communications link must be closed (i.e. sufficient SNR) on transmit and receive, which is what is represented by the EA and ESM illustrations in Figure 1.9.

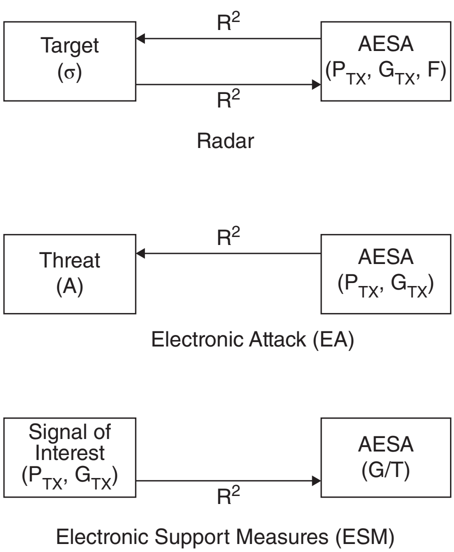

Figure 1.9 Illustration of the key performance parameters for an AESA that affect performance for radar, EA, and ESM.

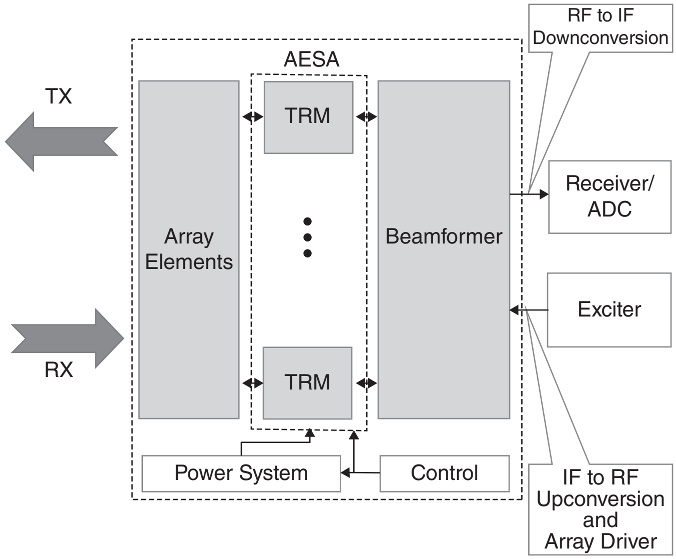

Figure 1.10 AESA block diagram highlights the major subsystems that comprise an AESA in addition to the backend electronics. These subsystems will be expounded upon in later chapters.

1.5 Block Diagram

With an understanding of how an AESA impacts SNR, the block diagram for a transmit receive (TR) system will be introduced that will be referenced throughout the remaining chapters. Figure 1.10 illustrates the relationship of how the AESA and backend electronics are connected. Effectively, the AESA can be simplified as an effective antenna with an effective HPA and LNA. This governs how the SNR will be affected. Traditionally in designing a system, the AESA will be flowed a requirement for total F, G, and P; this then is flowed down to the array elements, TRMs, and beamformer.

1.5.1 Antenna Array Elements

The antenna array elements are at the front end of the AESA. They directly affect the AESA antenna gain G in addition to polarization requirements. The array elements typically are either integrated with a radome or covered by an radome enclosure that is used to protect the elements from the environment. The radome is usually constructed to have minimal loss and also very small reflection for good transmittivity. Chapter 3 will provide a detailed explanation on the key array element performance parameters such as scan loss, active match, and insertion loss. The array elements also indirectly affect the requirement for P. For systems that transmit a large amount of power (radar and EA), the array elements must be able to operate without damage at high-power levels.

1.5.2 Transmit Receive Modules

The TRMs enable the AESA to electronically scan its beam(s) without a mechanical gimbal. They include phase shifters for beam steering, HPAs for transmitting, LNAs for receiving, circulators, filters, and switches. It will be shown in Chapter 4 that TRMs are responsible for ensuring that AESAs have graceful degradation and operate at requirement levels with failures. This is extremely important in terms of system reliability.

The TRMs effect on the SNR equation is on P_{TX} and F. The TRMs are the primary contributor toward maximum radiated power for maximal ERP and also drive the system sensitivity. For large arrays (>100 elements), the TRMs are typically the price driver for an AESA system. Great care is taken to ensure that they are optimally designed for minimized cost and complexity.

1.5.3 Beamformer

The beamformer for an AESA is a passive circuit whose role is to distribute the signal from the exciter to every array element and also to combine the signals received at every array element into a coherent sum beam. Passive beamformers directly affect P_{TX} and F and have to be optimized to minimize loss. Beamformers, as will be shown in Chapter 5, are also important for systems that do geolocation (radar, ESM, SIGINT). Multiple beamformers or a single beamformer with multiple outputs provide the receiver with sum and delta beams to enable geolocation.

1.6 AESA Cascaded Performance and Architecture Selection

Signal and noise gain, cumulative noise figure, cumulative intercept point, and spurious free dynamic range (SFDR) are all key peformance parameters for an AESA. Because of this, it is critical to understand how to calculate these parameters to effectively summarize AESA performance. Great care is taken in the design of an AESA to understand how all of the cascaded electronics operate together for overall AESA performance. Chapter 6 describes how to calculate these parameters with summary expressions to describe them.

Another aspect of AESA design is selecting the right architecture for different applications. As an example, AESAs that have a wide operational frequency bandwidth must be designed with a different architecture than an AESA that has a narrow band requirement. Chapter 7 covers the various AESA architectures that include analog beamforming, SA beamforming, overlapped SA beamforming, SA digital beamforming (DBF), and elemental digital beamforming (EDBF). These architectures provide a menu to select from to satisfy system level requirements such as operational bandwidth, IBW, maximum scan angle, and number of beams. Finally, adaptive beamforming will be discussed, which is a capability that is enabled by the SA DBF and elemental DBF architectures.

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