Reliability Advantages of Modular Solid State Power Amplifiers compared to Traveling Wave Tube Amplifiers

Stephen D. Turner, PE

PARADISE DATACOM, BOALSBURG, PA, 16827, USA

ABSTRACT

Mission critical systems demand the absolute maximum reliability possible. This high level of reliability is critical to military microwave amplifier systems. This paper shows how the modular design of solid state power amplifiers can provide dramatically higher levels of system reliability than traveling wave tube amplifiers. The HPA-20000 series from Paradise Datacom is a modular amplifier system that can provide up to 1.1 kW output power in C-Band (5.850-6.425 GHz) or 600W in X-Band (7.9 – 8.4 GHz).

Microwave Amplifier Technology

Amplifier manufacturers have long compared the advantages and disadvantages of solid state power amplifiers, SSPA, and traveling wave tube amplifiers, TWTA. Every few years there is typically a technology advance that gives a slight advantage to one technology over the other. For SSPAs, the advantage often follows an advance in Gallium Arsenide (GaAs) device technology. A higher power transistor enables the amplifier designer to increase the output power capability of an SSPA. On the other hand, solid state linearizer or predistortion circuits are now frequently used with TWTAs to improve distortion and make the TWTAs power transfer curve more closely approximate that of the SSPA. In recent years depressed collector techniques have improved the efficiency of TWTAs. Despite efficiency increases in SSPA and TWTA technology, both still suffer from relatively low overall efficiency. This requires both technologies to employ high-power, power supplies to operate their respective microwave devices. Anytime low efficiency circuits consuming high power levels are encountered, thermal design becomes a major concern. In fact, as the reliability of both tubes and transistors improves, it is noted that amplifier system failures are often due to power supply and thermally related problems.

Microwave Amplifier Architecture

The basic RF architecture of the SSPA is based on a parallel module design approach. Four SSPA modules are combined to achieve the desired output power level. The SSPA module is a complete amplifier system of its own in that it is comprised of a high gain (75 dB) system complete with a communication bus, gain adjustment, and a microcontroller. The parallel module concept is also extended to include the power supply. A simplified block diagram of the amplifier is shown in Figure 1. The modular architecture gives the amplifier system a degree of soft-fail capability that does not exist in the TWTA. There exists no single point of failure in any active component within the SSPA. If one module fails, the SSPA can continue to operate at reduced output power. The modules are also field replaceable, making system maintenance and repair possible. Contrast this to the TWTA, which typically has architecture as shown in Figure

2. The TWTA is a single electron tube amplifier, which is often in cascade with a small signal SSPA to boost the overall gain of the amplifier. The linearizer must also be in cascade with the TWTA, usually at the input. Therefore a failure in any one of the three major building blocks can result in the amplifier going off the air.

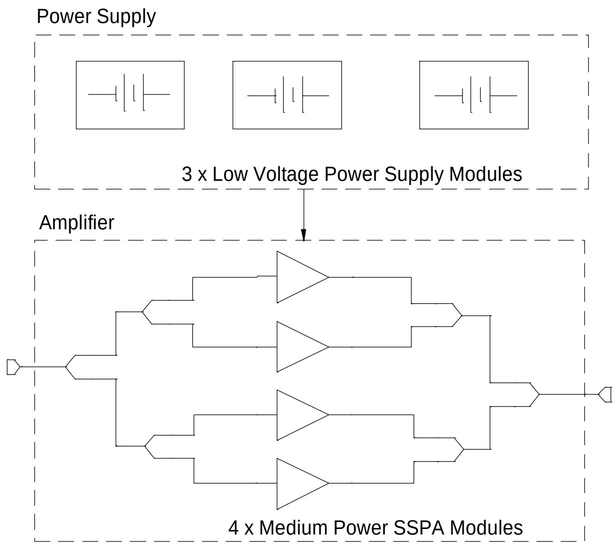

Figure 1. Solid State Power Amplifier (SSPA) Simplified Block Diagram

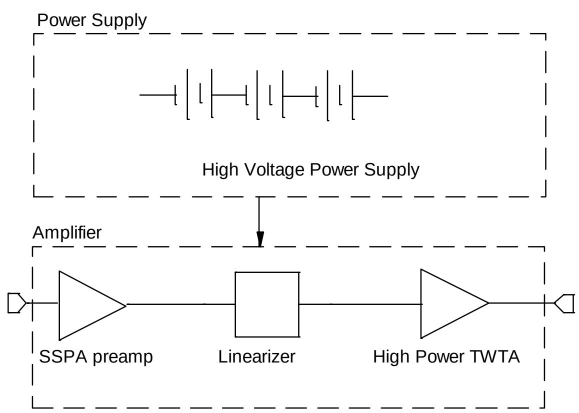

Figure 2. Traveling Wave Tube Amplifier (TWTA) Simplified Block Diagram

The SSPA also has a decided advantage in operating voltage. An SSPA typically operates with a DC voltage input in the +12 to +50 VDC range. At these low DC voltages there exists a wide variety of reliable power supply solutions. Several power supply vendors are producing modular N+1 redundant power supplies that can be used to operate the SSPA. This results in a degree of built-in redundancy in the power supply as well as the RF amplifier section. Conversely the traveling wave tube requires supply voltages in the several thousand volt range. This requires more complexity in the power supply subsystem. There are presently very few commercially available power supplies to choose from that produce these levels, much less provide the redundancy of a modular N+1 power supply. Therefore the basic architecture of the SSPA can provide significant reliability advantages.

Static Reliability Theory

Static models are often employed in system reliability analysis. They provide a useful preliminary form of reliability study before performing the more detailed calculations based on individual component reliability and statistical failure analysis. It is a block diagram level analysis in which each block is considered as being in one of two states: success or failure. The static reliability theory therefore determines a system's reliability based on the series and parallel architecture of the subsystem components. The most important concept of static reliability theory to grasp is that as the number of series components increases, the reliability decreases. This is commonly known as the product rule of reliability. The overall system reliability must be less than or equal to the least reliable subsystem. A parallel system is not considered failed unless all parallel branch subsystems have failed. Therefore anytime a parallel subsystem can be realized in a system, an increase in reliability will follow. For a system to be considered purely parallel there must be no switching to a standby subsystem. If a failure of a parallel subsystem occurs, there is no change to the reliability of the surviving subsystems. Where ***i***, is a particular subsystem in an overall system of n subsystems, the reliability functions are defined by the following equations.

$$R_S = \prod_{i=1}^{n} R_i \qquad \text{Series System Reliability}$$

$$R_P = 1 - \prod_{i=1}^{n} (1 - R_i) \qquad \text{Parallel System Reliability}$$

Reliability Model Development

From the simplified TWTA block diagram of Figure 2, the reliability model is a straightforward series model consisting of four subsystems (n=4). The reliability model takes on the form of Figure 3.

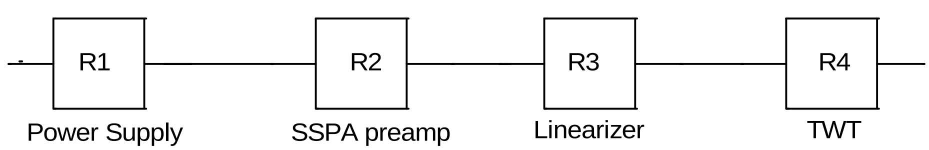

Figure 3. Series Reliability model of TWTA

For reference, an arbitrary subsystem reliability of 0.9 will be assigned to each of the blocks in Figure 3. This results in an overall system reliability of:

$$R_{TWTA} = \prod_{i=1}^{4} 0.9 = 0.6561$$

The solid state power amplifier is a hybrid system comprised of both series and parallel components. The parallel components are a special type of parallel system known as "n+1" redundant. This is to say that the individual subsystem requires n modules to be considered operational with one additional module. In the case of the power supply, two modules are required to operate the amplifier and one module is redundant. A failure of one power supply module will not cause the amplifier to fail. Therefore the power supply is a 2-out-of-3 parallel redundant system. This type of parallel redundant system is modeled as:

$$R_{r-out-of-n} = \sum_{x=r}^{n} \binom{n}{x} R^{x} (1-R)^{n-x}$$

where: n = total number of parallel modules
r = number of parallel modules required for system operation

$$\binom{n}{x} = \frac{n!}{x!(n-x)!}$$

Using the same arbitrary reliability of 0.9 for each power supply module, the overall N+1 redundant power supply reliability is 0.972. This is much higher than the reliability of a single power supply module.

The amplifier subsystem is structured so that a failure in one SSPA module can be tolerated and still achieve usable output power. Actually more than one module can fail and the amplifier will still produce output power however the power will decrease significantly. A failure in one SSPA module will result in a decrease of approximately 3dB output power capability. Therefore the SSPA is modeled as a 3-out-of-4 parallel redundant system. Using the same arbitrary reliability factor of 0.9, the SSPA subsystem reliability is 0.9477. Once again, this is much higher than the reliability of a single SSPA module. The reliability block diagram of the SSPA is shown in Figure 4.

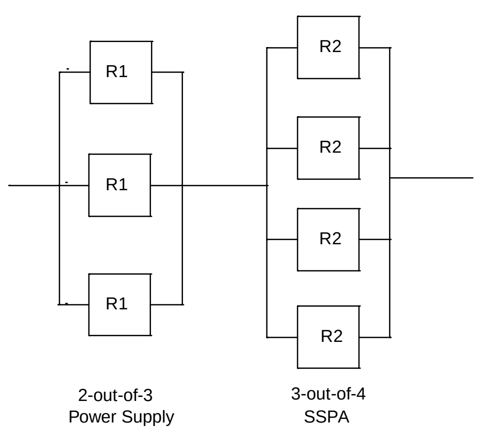

Figure 4. Hybrid (Series-Parallel) SSPA Reliability Model

The hybrid series-parallel system then reduces to the simple series redundant system of Figure 5.

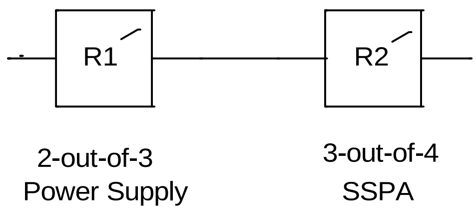

Figure 5. Equivalent Series SSPA Reliability Model

Using the equivalent series model for the SSPA with the parallel subsystem reliability values of 0.972 for the power supply and 0.9477 for the amplifier, the resulting system reliability is 0.9212.

$$R_{SSPA} = \prod_{i=1}^{2} R_i = (0.972 \times 0.9477) = 0.9212$$

Therefore a tremendous system reliability advantage results from the modularity of the solid state power amplifier system. This is based on the system architecture alone and does not involve the detailed reliability calculations of the individual subsystems. Based on system architecture alone, the TWTA can only ever achieve 71% of the reliability of the SSPA. This is assuming all individual subsystems of the TWTA and SSPA have the same reliability. Given the well documented high failure rates of tubes and their accompanying high voltage power supplies, it is reasonable to expect this value to become much worse when considering the actual cumulative distribution functions and MTBFs of these components.

Summary

Much has been written about the reliability comparison between TWTAs and SSPAs. These discussions often revolve around debates on individual component MTBFs. The MTBF debate is often vague and confusing in that the MTBF figures may be calculated or measured. Calculated MTBFs can be greatly skewed depending on the standard used such as MIL Handbook 217 or Bellcore (Telcordia TR-332) standards. Measured MTBFs can also be skewed, as there is presently no standard statistical measurement techniques agreed upon by suppliers of communication amplifiers. Combining this along with individual vendor bias makes it is nearly impossible to derive meaningful conclusions from supplier MTBF figures. This paper addresses the MTBF debate from a static reliability standpoint, thereby removing any discussion of MTBF data.

The static reliability analysis reveals that the concept of modular architecture in amplifier design provides dramatic system reliability advantages. Solid state technology is ideal for “n+1” style redundancy in amplifier systems. Although this paper compares solid state power amplifiers to traveling wave tube amplifiers, the modular architecture advantage would also apply to nonmodular solid state products as well. In TWTA design, it would be extremely difficult to implement modular architecture due to the high cost and complexity of the traveling wave tube. Additionally, to date there have been no commercially available modular power supplies developed at the high voltage levels required by the traveling wave tube. Paradise Datacom has shown that for equivalent operational RF output power levels, a modular solid state power amplifier can be produced for approximately the same cost as an equivalent traveling wave tube amplifier.

Paradise Datacom's modular, n+1, solid state power amplifier is packaged in a standard 19 inch wide indoor rack-mount enclosure. The enclosure is an impressive 6RU (10.5 inch) rack height. The modular power supply in housed in a separate 3RU chassis, making the complete amplifier system in 9RU of rack height. This small size makes it possible to realize phase combined and redundant systems using these amplifiers in a single cabinet. The power supply modules are hot-swappable in the field so that the amplifier system can never go off the air in the event of a power supply module failure. The SSPA modules are easily replaceable in the field for the ultimate in system maintainability. Figure 6 shows the Paradise Datacom modular amplifier system. Presently the modular system is available in the following frequency bands and output power levels.

C-Band, (5.850-6.425 GHz): 750W, 900W, 1100W
X-Band, (7.90-8.40 GHz): 500W, 600W
Ku-Band (14.0-14.5 GHz): 350W, 450W

Figure 6. Modular Solid State Power Amplifier System

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Author Biography

Stephen D. Turner, P.E., VP Engineering

Stephen Turner is the VP of Engineering for Paradise Datacom in Boalsburg, PA. USA.
He has been involved in the design of microwave components including: oscillators, amplifiers, and converters for over twenty years. He has introduced many innovative RF combining and thermal design techniques to solid state power amplifier design. Stephen received the BS degree in Electrical Engineering from the University of Pittsburgh and the Master of Engineering degree from the Pennsylvania State University. A registered Professional Engineer in Pennsylvania, Stephen is a member of the IEEE Microwave Theory and Techniques Society, Radio Amateur Satellite Corporation (AMSAT) and the Quarter Century Wireless Association (K3HPA). He can be reached at **sturner@paradisedata.com**.