Concepts in Communication Amplifier Redundancy Systems

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ABSTRACT

Redundancy is a major concern to satellite communication amplifier systems. This paper examines the various types of redundant systems used in satellite communication systems from a system reliability viewpoint. To overcome the ambiguities involved with comparing MTBFs, the paper discusses amplifier reliability based on static reliability concepts. Both traditional switched redundant systems and switch-less systems are compared.

Amplifier Reliability

Redundant systems of long been employed in communication amplifier systems as a means of increasing the amplifier system reliability. Redundant systems first appeared in communication systems with the introduction of the klystron amplifier. Generating high power microwave energy places tremendous electrical stress on the amplification device. Microwave klystron and traveling wave tubes (TWTs) operate at extraordinarily high cathode temperatures. These high operating temperatures result in relatively low MTBFs (Mean Time Between Failures) and thus a corresponding high failure rate. The high voltage power supplies required to operate traveling wave tubes also have a history of high failure rates. In recent years solid state power amplifiers (SSPAs) have made significant improvement in MTBF but still typically fall short of meeting the reliability expectations of satellite communication links. Satellite transponder time is extremely expensive and operators cannot afford to have a satellite link off the air for any period of time, no matter how short in duration. In many instances satellite equipment is installed in remote locations which are not easily accessed for maintenance. Therefore it is imperative that any amplifier system used in satellite communication be equipped with some form of automatic backup or redundancy. *The goal of any redundant amplifier system is to achieve a system reliability that is greater than the reliability of an individual amplifier.*

Static Reliability Theory

To simplify the understanding of amplifier redundancy concepts, the static reliability principles are applied throughout this paper. This removes the time varying probability density functions that can be based on many different types of distribution. The reader can choose to apply the probability density functions of choice to the results of the static reliability models to arrive at a Mean Time Between Failure (MTBF) figure of merit. The basic static reliability theory requires that series systems be modeled using the following equation.

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

Parallel system reliability is modeled using a form of the binomial distribution probability function that requires r-out-of-k components of a parallel system to be functional in order that the system is functional.

$$R_{r-out-of-k} = \sum_{x=r}^{k} \binom{k}{x} R^x (1-R)^{k-x} \quad \text{Parallel System Reliability} \qquad (2)$$

Where: k = total number of parallel modules
r = number of parallel modules required for system operation

$$\binom{k}{x} = \frac{k!}{x!(k-x)!} \qquad (3)$$

Amplifier System Redundancy

Redundant amplifier systems typically fall into two major categories: switched and switch-less. The switched redundant system is the more traditional type of redundant system and involves having a backup amplifier that can be switched on-line in the event of an amplifier failure. The most basic of redundant system is the traditional 1:1 redundant system. The 1:1 redundant system shown in Figure 1 is comprised of two like amplifiers. It consists of one amplifier that is normally on-line with one standby amplifier. The standby amplifier can be switched on-line if a failure in the on-line amplifier occurs. A transfer switch is typically placed at the input and output of each amplifier. Each amplifier has its own integral AC to DC power supply. In this system a controller must be involved to monitor each amplifier system's operating parameters for a fault condition. The controller could be a separate functional block of its own but in most cases is integrated into the embedded controller intelligence of each amplifier.

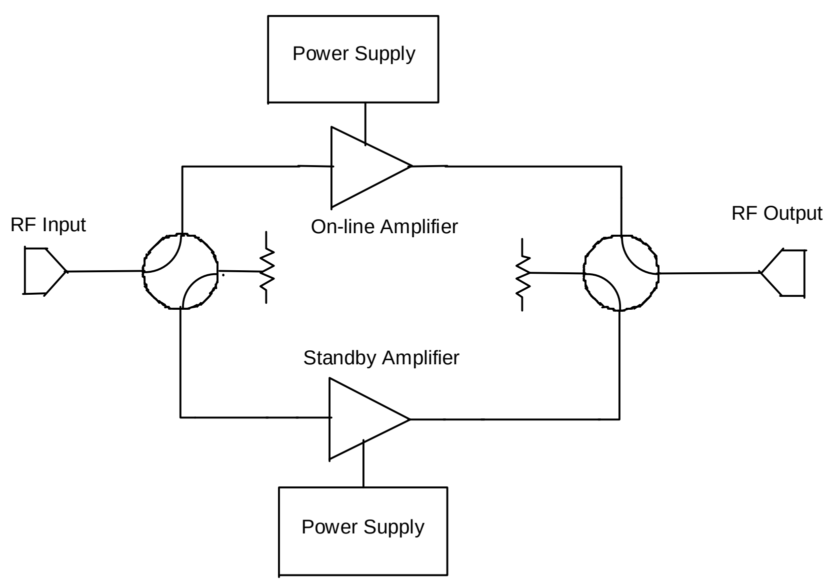

Figure 1. Traditional Switched 1:1 Redundant System

With the power supply in series with the amplifier, each amplifier thread in the redundant system is modeled as a series reliability system. For numerical comparison throughout this paper a reliability of 0.9 will be assigned to the power supply as well as the amplifier. The transfer switch is a single mechanical device for both the input and output and will be assigned a reliability of 0.95, slightly higher than the electronic based subsystems. Therefore each amplifier and power supply single thread subsystem would have a reliability given by the following equation.

$$R_{SingleThread} = \prod_{i=1}^{k} R_i = (.9) \bullet (.9) = 0.810 \qquad (4)$$

An ideal parallel combination of two $R_{SingleThread}$ systems in which at least one out of two subsystems must be functional in order for the system to be considered functional results in the following reliability.

$$R_{1-out-of-2} = \sum_{x=1}^{2} \binom{2}{x} R^x (1-R)^{2-x} = 0.9639 \qquad (5)$$

In a practical redundant system the switch reliability must be considered. The switch can be modeled in series with the resulting ideal parallel combination reliability. The complete redundant system reliability is then defined by the following equation. Thus the resultant redundant system reliability is considerable higher that that of a single thread subsystem.

$$R_{1:1System} = \prod_{i=1}^{k} R_i = (.9639) \bullet (.95) = 0.9157 \qquad (6)$$

Comparing equation 6 to equation 5 shows the effect that the switch reliability has on the overall system reliability. This suggests that if a redundant system could be configured without a transfer switch, an improvement in reliability may be realized.

Modular (Switch-less) Redundancy Techniques

Next consider a system comprised of a 2-out-of-3 modular power supply feeding a 3-out-of-4 modular amplifier system. This type of system is gaining in popularity and is shown in Figure 2.

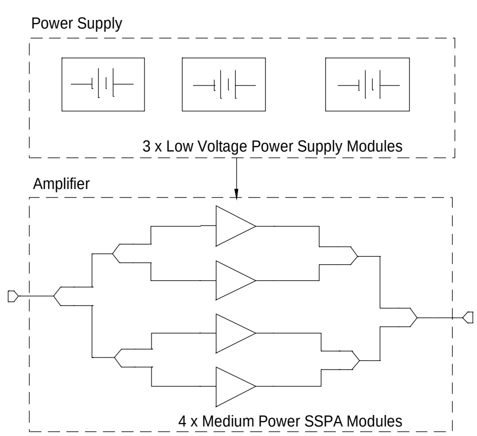

Figure 2. Solid State Power Amplifier (SSPA) Simplified Block Diagram

Such a system yields a power supply reliability given by the following equation.

$$R_{2-out-of-3} = \sum_{x=2}^{3} \binom{3}{x} R^x (1-R)^{3-x} = 0.9720 \tag{7}$$

Similarly for a four module amplifier with strictly passive power combining the resulting reliability is given by equation 8.

$$R_{3-out-of-4} = \sum_{x=3}^{4} \binom{4}{x} R^x (1-R)^{4-x} = 0.9477 \tag{8}$$

Finally using the series combination of the two subsystems, the total system reliability is given by Equation 9.

$$R_{4\text{mod}\,uleSystem} = \prod_{i=1}^{k} R_i = (.9720) \bullet (.9477) = 0.9212 \tag{9}$$

Therefore the system reliability of the four amplifier module system is greater than any of the individual components. In fact it is even greater than the traditional, switched, 1:1 redundant system.

RF Output Power Considerations

It is important to examine the RF output power implications of using the modular amplifier as a redundant system. In the traditional 1:1 redundant system it was shown that the switch had the affect of reducing the system reliability. The switch does however offer the advantage that there is no loss of output power capability in the event of one single thread subsystem failure. This is in contrast to the modular amplifier system which utilizes a passive RF output power combining array. The passive combiner has the advantage of not reducing the system reliability but suffers the disadvantage of decreasing the RF output power capacity in the event of an amplifier module failure. One amplifier module failure results in an RF output power reduction of 3 dB. If the four module amplifier system to be considered as a redundant system, it must be sized to have 3 dB excess output power capability or twice the RF output power of the traditional 1:1 switched redundant system. This 3 dB margin is generally an acceptable margin both from a functional as well as economical standpoint.

An ideal parallel system of two amplifier modules would give excellent reliability but unfortunately is not practical from a passive RF combining viewpoint. In this case an amplifier failure would result in 6 dB reduction of output power capability, or a factor of 4 times the output power. This would be considered excessive enough as to have to consider the entire system as having failed. For many operators, it is economically prohibitive to purchase 6 dB of output power margin in a high power amplifier system.

It is tempting to consider constructing an amplifier with a greater number of amplifier modules so that there is less than the 3dB reduction in output power in the event of a module failure. As more modules are combined, the loss of any one module results in much less percentage of the total output power capability. High power RF combining is typically realized in binary combinations. Thus the next logical quantity of RF amplifier modules to consider is 8. With 8 modules used in a binary combiner, a loss of one amplifier module results in a reduction of about 1.5 dB in output power capability. The less output power capability that is lost in the event of an amplifier failure means that much less capacity needs to be purchased. A block diagram of an eight amplifier module system is shown in Figure 3.

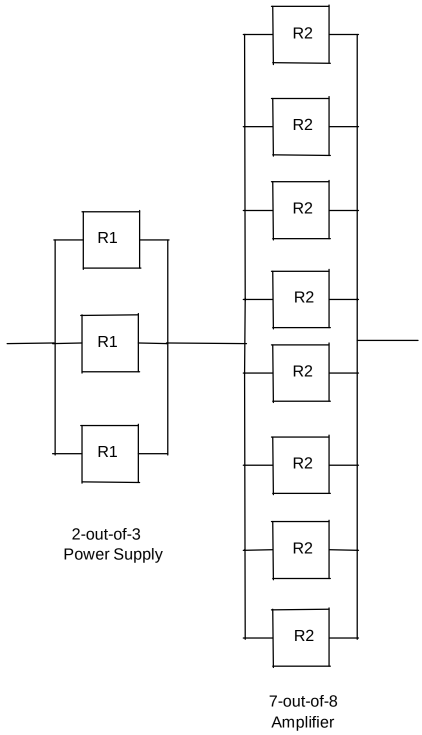

Figure 3. N+1 Redundant System comprised of 8 Amplifier Modules

Here the power supply reliability is the same as the previous amplifier example (.9720) represented in equation 7. The amplifier reliability is defined by equation 7 for a 7-out-of-8 parallel system.

$$R_{7-out-of-8} = \sum_{x=7}^{8} \binom{8}{x} R^x (1-R)^{8-x} = 0.8131 \qquad (10)$$

The resulting system reliability is then defined by equation 11.

$$R_{8\,\mathrm{mod}\,uleSystem} = \prod_{i=1}^{2} R_i = (.9720) \bullet (.8131) = 0.7903 \qquad (11)$$

As equation 10 reveals, the amplifier system reliability is less than any of the individual amplifier modules. Further when the total system reliability is considered it turns out to be much less than the 4-module amplifier system. With such a low reliability figure the 8-module system could not be practically considered as a redundant system in terms of sizing the power capacity for a single RF module failure. A closer look at parallel reliability systems is required.

Parallel System Reliability Considerations

The system designer must exercise caution when considering the reliability of parallel systems. The parallel redundant systems discussed thus far are a special type of r-out-of-k system sometimes referred to as "N+1" redundancy. In other words, the system is designed so that N modules are the minimum required for the system to be operational. This leaves one module to operate as a hot standby module, giving the system its redundancy. In the case of the system power supply, only two modules are ever required to operate the amplifier. One power supply module is operating in hot standby. In the event of a power supply module failure there is no reduction in service as the two remaining modules can supply the full power required by the amplifier. The amplifier scenario is slightly different in that a module failure will result in a loss in output power capability. The operation of a communication amplifier is such that it is rarely operated at its maximum output power capability. There are several reasons for this including keeping reserve power for fade conditions and keeping distortion products at a very low level. It has been shown that as more amplifier modules are added to an amplifier system; there is less reduction in output power upon a single module failure. But as more modules are added to the amplifier, the reliability of N+1 redundancy decreases rapidly. Therefore the design of a parallel N+1 redundant amplifier system is a delicate tradeoff between the reduction in output power capability and the reduction in system reliability that can be tolerated.

Figure 4 shows the relationship between system reliability and individual component reliability for various r-out-of-k configurations. A 16 module system is also shown for comparison. Note the decrease in system reliability for systems comprised of more than 4 modules. It is also alarming to note the accelerated decrease in system reliability as the individual module reliability decreases.

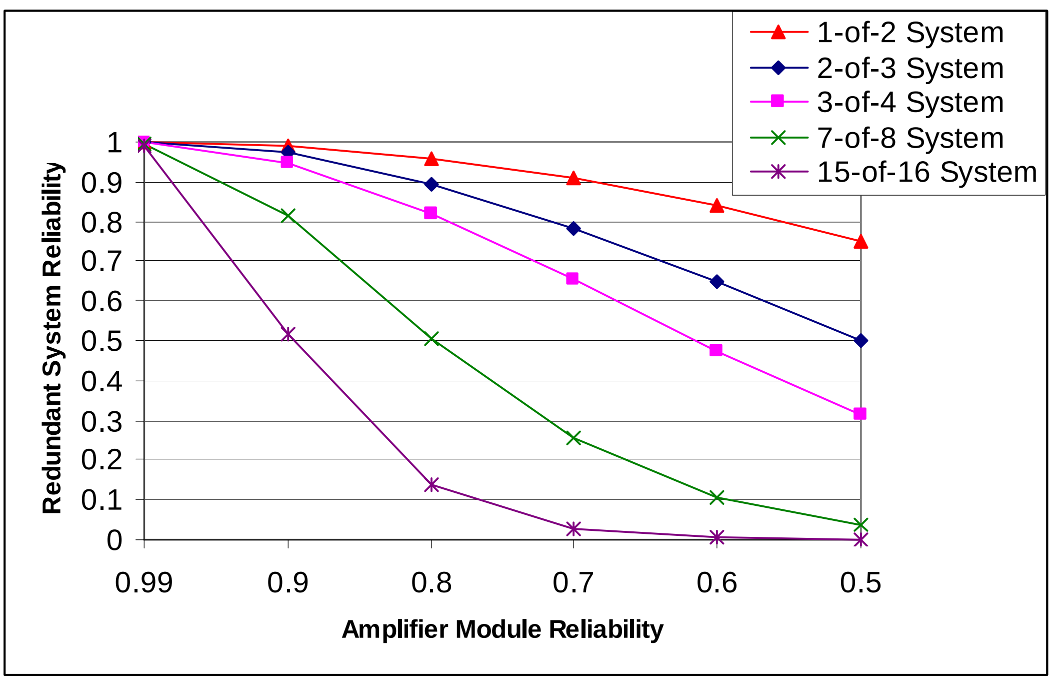

Figure 4. (N+1) System Reliability vs. Module Reliability for various r-out-of-k Configurations

From Figure 4 it is obvious that the larger systems comprised of 8 and 16 modules cannot be considered “N+1” redundant based on the necessary reliability required from a redundant system. The basic definition of a redundant system requires that the system reliability be greater than the reliability of its individual components. Figure 5 shows the 8 and 16 module reliability curves with adjusted values of ‘r’ so that their reliabilities can as high as the 4 module system. The 8 module amplifier system must have 6 of its 8 modules active to achieve the reliability as defined by a redundant system. The 16 module system must have 12 of its modules functional to achieve the reliability of a redundant system. Therefore an 8 module amplifier system must be considered an “N+2” redundant system. Similarly the 16 module system would be an “N+4” redundant system.

This requires rethinking the redundant output power capability of these larger systems. Recalling the binary nature of the passive RF power combining, each of the larger systems would actually have the same redundant RF output power capacity of the 4 module system. Two module failures in an 8 module system would result in a 3 dB reduction in output power capacity. Four module failures in a 16 module system would result in a 3 dB reduction in output power. It can be concluded that for any parallel module amplifier system, utilizing passive binary combining, to be considered a redundant system, it must have two times the required output power capability.

As a practical example consider that a traditional 1:1 redundant system comprised of two 500W amplifiers would have the equivalent reliability and redundant output power capacity as a 4 module, 8 module, or 16 module 1.0 kW modular amplifier. Then considering the economics of the purchase price of these choices places a huge advantage in favor of a 4 module amplifier system. The 4 module amplifier system achieves the best combination of performance, price, and reliability. Table 1 summarizes the comparison of a 500W redundant solid state amplifier system for C Band microwave service.

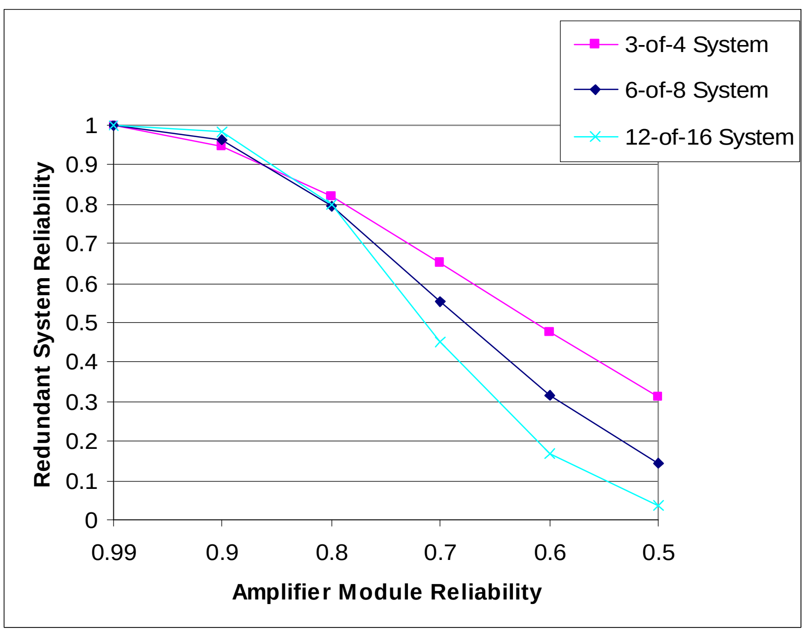

Figure 5. (N+x) System Reliability vs. Module Reliability for various r-out-of-k Configurations

Table 1. 500W C-Band Redundant Amplifier System Configuration Comparisons

Amplifier System	Redundant Output Power	Reliability	Approximate Cost
Traditional 1:1 System with two 500W amplifiers	500 W	0.9157	$ 92,000.00
4-Module 1 kW System	500 W	0.9212	$ 85,000.00
8-Module 1 kW System	500 W	0.9619	$ 100,000.00
16- Module 1 kW System	500 W	0.9829	$115,000.00

Summary

Redundant amplifier systems have long played an important role in both terrestrial and satellite communication systems. The redundant system allows the system engineer achieve greater reliability from the system than would be achievable with a single thread amplifier. This paper examined the reliability of both switched and modular (switch-less) redundant systems. Properly applied the modular amplifier system can be an attractive alternative to configuring system redundancy. Lower cost and less rack space are some of the advantages of a modular amplifier system.

The ability to have RF output power margin in a system link budget can make the modular amplifier an attractive alternative for redundant system configuration. When comparing modular amplifier products it is important to understand the output power reduction and reliability of the various configurations. It has been shown that the 4 module passive power combined amplifier system is both an economical and reliable alternative to traditional switched redundant systems. A single amplifier chassis can be considered as a redundant amplifier system. The 3 dB excess output power capability can be useful for periods when some extra power reserve is required. Paradise Datacom has a complete product line of 4-module amplifier chassis covering sitcom frequency bands. The amplifier chassis is a 6RU (10.5 inches) rack height while the power supply is a 3RU chassis, making the complete amplifier system in 9RU of rack height. 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. 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. 4 Module Amplifier / 3 Module Power Supply System

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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**.