Adaptive Techniques to Improve the Efficiency of GaN Based SSPAs (up to C Band) for Geo Synchronous Satellites

by

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Declaration

I hereby declare that

1. the thesis comprises my original work towards the degree of Doctor of Philosophy at Dhirubhai Ambani Institute of Information and Communication Technology and has not been submitted elsewhere for a degree,

2. due acknowledgment has been made in the text to all the material used.

Ramesh J Doshi

Certificate

This is to certify that the thesis work entitled "Adaptive Techniques to Improve the Efficiency of GaN Based SSPAs (up to C Band) for Geosynchronous Satellites" has been carried out by Ramesh Jasvantlal Doshi for the degree of Doctor of Philosophy at *Dhirubhai Ambani Institute of Information and Communication Technology* under my supervision.

Prof. Deepak Ghodgaonkar

Thesis Supervisor

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Abstract

In this thesis, various adaptive techniques to improve the efficiency of Solid State Power Amplifier (SSPA) for Geo Synchronous Satellite are presented. The Microwave Power Amplifiers (MPAs) being the most important sub-system determining payload weight, volume, cost and many important link parameters, their performance is improved by novel techniques. Out of various techniques available, the important techniques like flexible (adaptive) output power, flexible frequency and bandwidth, flexible thermal management, adaptive temperature compensation, replacement of Travelling Wave Tube Amplifiers (TWTAs) by Solid State Power Amplifiers (SSPAs) and improvement of reliability of SSPAs are presented in detail.

Literature survey on reported techniques to reduce the cost of the satellite services, making the satellite payload flexible and development of newly emerging technology, Gallium Nitride (GaN) based SSPAs to replace the TWTAs are included. The recent development on a new technique so called flexible payload or adaptive payload is described. This new architecture known as of Generic Flexible Payload (GFP) has been proposed by European Space Agency and Astrium, which allows to meet various requirements like evolving business and political landscapes, the emergence of new technologies and applications, or even a change of orbital location or owner. The adaptive or flexible payload allows the user to redefine the frequency plan, redistribute the transmit power between service regions and change the EIRP according to the specific need without scarifying the satellite performance.

Recent development on GaN based SSPAs by various authors are also included. SSPA being the complex sub-system, especially for Geo-Synchronous Satellite, major specifications including Reliability and Quality Assurance criteria are described in detail. The nominal value of each parameter for 200 watt GaN based SSPA is also given.

The Power Added Efficiency (PAE) is the critical parameter for selection of high power amplifier for space segment. TWTA has been selected so far due to its' higher efficiency than the SSPA. Moreover, the efficiency decreases drastically for both type of amplifiers under back off operation, so it is necessary to improve the efficiency of the amplifier under back off. The state of the art device technology device, GaN HHET has been selected to demonstrate the concept of flexible output power SSPA, also called "SSPA with Dynamic biasing technique". Theoretical analysis of efficiency of SSPA at saturation and at back off has been presented and shown that the efficiency degrades at back off. To improve the efficiency, the

drain voltage can be varied according to the RF input drive level and the data has been programmed in the EEPROM controller. Non-linear simulation including Harmonic balance simulation and load pull characterization has been presented using non-linear model of GaN device on Agilent's Advance Design Software (ADS) platform. The proposed work is compared and discussed with the reported work. The results for 200 Watt and 20 Watt SSPA flexible SSPA at various back off including EEPROM controller are discussed.

Another novel technique to change the frequency of operation and bandwidth of SSPA on-board using tele command from ground is described using all microwave amplifying semiconductor devices. Theoretical background behind the concept of adaptive frequency amplifier is discussed in detail. Non-linear simulation, load pull counters and measured results of 100 Watt UHF SSPA, using Si RF MOSFET are presented in the thesis. The simplest technique to change the frequency of the SSPA from the ground is also described with the measured results. In addition to meeting The important aspect of this research is to improve the efficiency of the SSPA in addition to provide the flexibility in terms of frequency. Hence, the results of efficiency improvement in case of narrow band SSPA as compared to wide band SSPA are also presented.

In addition to above two techniques, another new technique to improve the efficiency of SSPA by providing flexible thermal management system. The present balance configuration of final power amplifier is modified with single ended device configuration and reliability calculations are proposed using real time temperature data. Finite Element Model (FEM) analysis is carried out for both the options and thermal counters are generated using IDEAS software. Detailed study on degradation of performance of material used for thermal management system, design challenges and efficiency improvement results are described. The similar concept has been applied to make the temperature compensation adaptive by which the gain and output power variation over the specified temperature range can be adjusted as per the requirement after launching the satellite.

For satellite communication payload, the power amplifiers generate third order intermodulation distortion (non-linearity) under multi-carrier operation so its' accurate characterization is necessary. The usual practice of measuring this non-linearity is not accurate so the results are non-consistent and hence, the SSPA has to be operated in linear region, which degrades the efficiency. A novel technique is presented in this thesis, which gives accurate measurement so that the SSPA can be operated near saturation resulting in improvement of efficiency.

The TWTAs have been used in the satellite payloads since the beginning of the satellite technology and found to be most reliable. Now when the SSPA developers are putting efforts to replace them, it is very important and necessary that the newly developed SSPAs are also having the reliability at par with the TWTAs. Many failures have been reported during the development of GaN device and GaAs FET devices were also failed during initial phase, so it is mandatory for SSPA designer to launch the SSPA with highest reliability. A new approach is presented to provide highest reliability with various techniques implemented. These techniques will help to understand the failure if any, and to modify the operating condition of the GaN transistor.

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CHAPTER 1
Introduction

1.0 Introduction

The satellite communication is the most reliable way of communication with highest availability. But the present Satellite Communication Technology is suffering from two major drawbacks such as

(1) Compared to terrestrial gateways, the satellite based solutions are very costly. Satellite launching cost, acquisition, control and maintenance are very costly due to heavy mass and volume of the satellite payload. The payload mass, volume and cost is mainly determined by the Microwave Power Amplifiers (MPAs) like Travelling Wave Tube Amplifiers (TWTAs) and Solid State Power Amplifiers (SSPAs) which are of large mass and volume. Larger amount of weight puts limit on the amount of the fuel which can be filled in the satellite and hence reduces the life of the satellite and increases the cost.

(2) Moreover, the defined performance is unaltered (fixed) for the proposed satellite life of 10 to 15 years. But as the space segment performance is fixed one cannot be satisfied with existing satellites onboard or has to wait for new satellite to be launched. It becomes very difficult for the operator to plan a robust business case over such long period

About 90 % of the payload mass, volume and power is contributed by High Power Amplifiers. The power amplifiers designed so far in any of the communication system (ground or space) has been suffering from various limitations due to the various reasons like,

(i) Fixed output power with lower efficiency at back-off

(ii) Fixed operating frequency band (Broad bandwidth to cover multi-band frequencies)

(iii) Higher channel temperature for solid state technology limiting the life of operation

As compared to the ground, these limitations are of great concern for Geostationary Communications Satellites because the defined performance is unaltered (fixed) for the proposed satellite life of 10 to 15 years. However, evolving business and political landscapes, the emergence of new technologies and applications, or even a change of orbital location or owner, can alter the operational requirement on the payload. But as the space segment performance is fixed one cannot be satisfied with existing satellite onboard or has to wait for new satellite to be launched. This requirement leads to a new architecture so called Flexible Payload.

This payload allows the user to redefine the frequency plan, redistribute the transmit power between service regions and change the EIRP according to the specific need without scarifying the satellite performance. The High Power Amplifier (HPA) being the major contributor for EIRP, some new techniques need to be implemented for improvement in its performance.

The power amplifier (PA) designer has to face many challenges (either for ground base application or space environment application) as the overall performance of the communication system depends upon it. Due to higher power handling, it consumes maximum DC power and also dissipate maximum power as heat leading to many issues related to thermal management, increased weight and cost. Especially for space applications it is operated in multicarrier condition as well as has to withstand unwanted overdrive signal so it determines linearity and the reliability (useful life) of the overall system. The most common example is the mobile handset whose weight, cost and useful life is decided by the battery.

As compared to the fixed (static) performance PA, a reconfigurable (flexible) PA can be designed to improve its performance especially efficiency and reliability for geo satellite communication.

The TWTA is vacuum based amplifier operating at very high voltage (10000 volts) so it is very difficult to modify its design to change the output power, frequency of operation and thermal management. SSPA being low voltage operating device (up to 50 volts) so can be made adaptive easily as compared to TWTA, hence it is selected for designing adaptive amplifier. Due to higher mass, volume and cost of the TWTAs, the overall cost of the payload increases so it is necessary to replace the TWTAs with SSPAs but as compared to TWTA, SSPA has poor efficiency and has seen many failures in past so it is necessary to improve the efficiency as well as reliability of the SSPA.

1.1 Basic Characteristics of the Adaptive SSPAs:

The performance of any sub-systems cannot be changed once it's design and fabrication is completed so whenever any new emerging technology arrives in the market, it is not possible to satisfy the users' demand for new technology. The ground based hardware can be modified or replaced which may not be much costly solution, but for space base hardware, it is not possible to modify and replace. Because of such rigid nature of the space based sub-systems, the space based solutions are very costly as compared to terrestrial solutions. So for survival of the satellite technology, it is necessary to reduce the cost and to provide flexibility to satisfy users' demand for state of the art technology. As described above, providing flexibility in SSPA will meet both the requirement. The flexible or adaptive SSPA is designed such a way that it is possible to change the output power without much degradation of efficiency and to change its operating frequency as well as operating bandwidth by issuing command from the ground. It is also possible to modify the configuration by switching to improve the efficiency as well as reliability. These features allow flexibility in addition to the improvement in efficiency.

1.2 Challenges:

As compared to the ground application, the subsystem designed for space application has to take care of critical challenges such as on-board DC power generation, removal of dissipated power as heat, thermal management, Multipaction and corona due to vacuum operation, ionizing radiations, availability of space qualified components, reliability guidelines and non-repairable hardware. Besides these challenges, the following complexity and challenges are involved in providing the flexibility in high power amplifiers.

(a) So far the microwave power devices manufactured by the manufacturer were internally matched to 50 ohms over the wide bandwidth so it was not possible to change their performance externally. To meet the requirement of flexibility, the unmatched devices have to be used. The power devices are having very low impedances and poor (VSWR) return loss which leads to special matching techniques like Non-linear (Harmonic Balance) Simulation for varying source and load impedances.

(b) The high power devices have to be matched to satisfy the unconditional stability criteria under all source and load conditions. When used for adaptive technique, the device impedance will vary which me lead to unstable operation of the device. A great challenge lies in providing perfect matching under varying source and load impedances while maintaining the device efficiency.

(c) Device selection itself is a great challenge for space segment due to various constraints like de-rating of all parameters, operating temperature range, non-repairable system, reliability etc. With advancement of emerging technology of wide band gap Gallium Nitride (GaN), it is now possible to design high power SSPAs but the GaN technology has also seen many failure during its realization phase so careful decision is required before these devices are used for space.

(d) It is very essential to maintain the gain of the transponder chain with varying impedances and frequencies.

(e) Switching using Varactor and PIN diode needs accurate non-linear modeling and to change their bias remotely is a great challenge for space segment.

Implementation of all above techniques will improve the efficiency and reliability in addition to providing flexibility of the SSPA for space use. The above challenges have been understood and successfully resolved by using new techniques and new device technologies.

1.3 Historical Developments of Adaptive SSPAs:

The SSPA, since its birth in RCA Laboratory is struggling to compete the long heritage TWTA. In 1988, the 4 Watt C-Band TWTAs were replaced by GaAs based SSPAs in many Geo stationary satellites. This achievement was believed to be the end of TWTAs' era. But unfortunately, there were failures observed on board in SSPAs due to use of Aluminum gate structure of GaAs FETs. Metal migration was serious issue due to which many devices failed on board and again the solid state technology was in question. The problem was understood, demonstrated and resolved on ground and hence the aluminum gate was replaced with gold gate. After thorough investigations of the failure mechanism, it was established that when the final power devices were operated at higher gain compression (3 to 4 dB) the gate metal (Aluminum) diffused into source. Later, the Aluminum gate was replaced with Gold metal and proved to be the right solution to the problem. Since then, the SSPAs with Gold gate GaAs MESFETs are operating satisfactory on board and have successfully replaced TWTAs up to lower power levels of 15 watts at C-and and 40W at L-band. To meet the increasing demand of higher EIRP and higher bandwidth, GaAs MESFET devices were not capable of delivering higher power with higher efficiency amplifier due to their lower drain voltage (lower energy band gap). The approach of combining many devices resulted in poor efficiency so the SSPA technology was again in question. Recent development in GaN Heterojunction FET (HFET) has encouraged the SSPA designers to replace TWTAs for UHF, L, S, C and X Band.

The concept of flexible payloads was proposed in early days but could be realized very late due to lack of suitable variable components. For ground based sub-systems, this concept has been demonstrated nut for space based sub-systems, European Space Agency (ESA) and Astrium have demonstrated which is described in the next section.

1.4 Motivation:

Interest in flexible payload technologies has grown significantly over the last few years.
Astrium is at the forefront of technology development for analog and digitally processed flexible payloads.
Research towards the program of The Generic Flexible Payload (GFP) was undertaken between the European Space Agency (ESA) and Astrium.
The primary goal of the program is to design, develop, and qualify an active flexible input (receive) section which allows the payload to be as transparent as possible.
In this GFP architecture, the output (transmit) section is not planned to be flexible and hence wideband TWTAs are shown in its block diagram.
As Astrium plans and executes its research and development activities for the future processor capability, the architecture from GFP program provides capability for offering agile processed payloads providing the highest levels of flexibility and generosity.
These together with flexible coverage and power flexibility enable the vision of a truly generic flexible payload.
Thus, it is clear from above discussion that flexible payloads are of great commercial interest so the design and implementation of the flexible payload need to ensure the optimum balance between the levels of flexibility provided and cost, mass, power etc.
For geo-satellites, the input (receive) section is of reverse nature as compared to output (transmit) section that involves various complexity such as need for higher DC power, higher thermal dissipation, highly non-linear and availability of space qualified components.
Hence, to provide flexibility in the transmit section is of great challenge and research towards this area is necessary.

1.5 Objective of the Research:

The prime objective of this research is to reduce the cost of the satellite base solutions. The cost can be reduced by increasing the life of the satellite or by increasing number of the users. For increasing the life of the satellite, more amount of fuel should be filled but again it will increase the weight and hence cost. So it is necessary to reduce the weight of the other sub-systems and also make them more efficient so that lesser amount of DC power has to be generated on board. As described above, the Power amplifiers are the major role player determining the cost, so the prime objective of this research is to improve the efficiency of the power amplifier and reduce the weight of the power amplifiers. The TWTAs are more efficient than the SSPAs but are heavier (almost double weight and volume), so it is necessary to design SSPA with higher efficiency and lesser weight and volume to replace the TWTAs. Out of various techniques available, following four techniques were studied and implemented to achieve the required flexibility in terms of output power, frequency of operation, thermal management and improvement in efficiency as well as reliability. Three different types of the devices used for high power SSPAs are chosen for the design.

(1) Flexible output SSPA

The newly emerging device technology of Gallium Nitride (GaN) HFET has been described and the same has been selected to demonstrate the complexity involved in the design, optimization and simulation. This amplifier has been used for implementation of new technology called flexible output power amplifier. The measured results of 180 Watt L and S band SSPA using GaN device has been presented.

(2) Flexible frequency and bandwidth SSPA

The existing device technology of Si RF MOSFET and GaAs MESFET has been selected for design, optimization and simulation. These amplifiers have been used for implementation of new technology called flexible frequency or switching amplifier. The PIN diode and Varactor diode used for modeling as well as hardware realization are having good space heritage. The measured results of 40 Watt UHF band SSPA has been presented.

(3) Improving the efficiency of the SSPA by flexible thermal management.

All SSPAs designed so far have the fixed thermal limits over which they are operated and hence the thermal analysis is also carried out for the worst case base plate temperatures, not the actual operating temperature. The thermal analysis can be made as per real time base plate temperature which will result in saving of a remarkable amount of DC power and reduction in the thermal power dissipation by switching at device level. This concept has been demonstrated for 100-watt UHF SSPA as well as 150 Watt GaN Based L-Band SSPA. The similar concept has been applied to make the temperature compensation adaptive by which the gain and output power variation over the specified temperature range can be adjusted as per the requirement after launching the satellite.

(4) Reliability improvement techniques in SSPA

The TWTAs have been used in satellite payloads since the existence of the satellite communication technology and are proven technology so when this long heritage technology is replaced with solid state technology, especially at higher power, it is necessary to ensure the highest reliability of this new technology. Research towards improvement of reliability of GaN based SSPA is carried out and has been demonstrated successfully.

1.6 Organization of the Thesis:

Nine chapters of the thesis are organized as below:

Chapter 2 presents the literature survey of the reported work related to the adaptive techniques implemented to make the payload flexible, state of the art development on GaN based SSPAs.

In chapter 3, technical specifications of a typical SSPA designed using GaN HFET for geo synchronous satellite are given including detail description of each parameter. Reliability and Quality Assurance aspects and the environmental test conditions are also described.

Chapter 4 introduces a new technique to make the SSPA flexible in terms of output power. New emerging technology device, GaN has been selected for design of 200 Watt flexible SSPA. Non-linear simulation is presented using non-linear p-spice model of GaN HEMT device. EEPROM controller is also discussed and the technique to change the drain voltage of the device is presented here. In addition to achieve the flexibility, another advantage of improvement in efficiency at back off is discussed in detail.

Chapter 5 gives detail of adaptive frequency SSPA for changing the frequency and bandwidth of SSPA on-board. The SSPA is designed using Si RF MOSFET at UHF band, GaAs MESFET at C-Band and Ku-Band and also GaN HEMT at S-Band. Load pull counters for efficiency, intermodulation and output power are drawn and discussed in detail to present the concept of flexible frequency SSPA. A technique to change the bias of the active devices is also presented for on-board applications.

In Chapter 6, a novel technique is presented to improve the efficiency of SSPA using real time temperature data of the device case temperature. As compared to the existing method of channel temperature calculation at worst case temperature, this new approach will improve the efficiency during half the life of the satellite. Various configurations are discussed including the thermal counters using FEM analysis. An adaptive Temperature Compensation technique is also presented based on the similar concept.

Chapter 7 describes another technique to improve the efficiency of SSPA under the multi-carrier operation for geo-synchronous satellites. The SSPA or TWTA is the non-linear sub-system operating at saturation in the communication transponder so contribute to the overall non-linearity of the satellite communication system. Accurate measurement of the third order inter modulation product is necessary to achieve the most optimal performance of the transponder. An accurate and repetitive measurement technique of third order inter modulation product is presented.

In Chapter 8, a simple approach is presented to improve the reliability of the newly developed GaN based SSPA. Various techniques are presented to take care of any failure observed on-board and also to understand the behavior of GaN HFET in the geo-synchronous satellite atmosphere.

CHAPTER 2
Literature Survey on Adaptive techniques to Improve Efficiency of SSPAs

2.0 Introduction:

When the satellite communication technology was in its childhood, the space segment was made as simple as possible and the ground segment (user terminal) was much complex. The communication was in FSS (Fixed Satellite Services) and BSS (broadcast Satellite Services) mode, between fixed (stationary) terminals only. Later, as the demand of satellite communication increased, there was a need for moveable user terminals for MSS (Mobile Satellite Services) and hence the sizes of the user terminals need to be reduced. With advancement of technology, the scenario has been reversed so it is a great challenge for satellite communication industry to satisfy the users' demand. The business cases for new communications missions are under constant pressure from both competitions within the space segment and also from terrestrial solutions. The users continuously demand more and more bandwidth and higher signal strength (EIRP) at a lower cost whereas the available spectrum is becoming scarcer due to limited orbital slots, frequency allocations and adjacent satellite interference issues. [1] So it is a great challenge for satellite communication to survive as the satellite based solutions are very costly compared to terrestrial gateways. This calls for development of new techniques by which users need can be satisfied and the cost can be reduced.

The cost can be reduced by two ways, (i) by increasing the life of the satellite and (ii) by increasing the number of the users.

For the first case, by increasing the design life, the cost per bit can be reduced but it becomes very difficult for the operator to plan a robust business case over such long period. Moreover, the defined performance is unaltered (fixed) for the proposed satellite life of 10 to 15 years so the users' demand of updated services cannot be satisfied and objectives of post-mission changes are not possible and hence they have to wait for new satellite to be launched. Hence, there is a need for achieving an adaptive satellite link performance that meets the mission and post-mission objectives through a careful and objective selection of satellite system parameters as post launch modification is not possible [2]. One important factor determining the life of the satellite is the fuel carrying capacity. So to increase the life of the satellite, larger amount of the fuel should be carried which will increase the launching cost (The launching cost for one-kilogram weight is about 50000 USD). Hence, it is necessary to reduce the weight of the other sub-systems to increase fuel capacity.

For the second case, it is necessary to maximize (increase) the number of the users for the satellite so that cost can per user can be reduced. In [3], the problem of maximizing the number of users served has been addressed and in [4], an improved dynamic power allocation algorithm has been proposed which can serve even more number of users.

Out of these two cases, there are more opportunities in the former case as required techniques can be implemented in the sub-systems during design phase itself looking at the future requirements and can be used as and when required so that the cost can be reduced in addition to providing the users' demand for state-of-the-art services as compared to the second option.

In order to keep the satellite users updated with the changing market trends and to reduce the cost, it is necessary to replace the present satellite sub-systems which are fixed or rigid in terms of performance by flexible or adaptive sub-systems.

Such concept called "Generic Flexible Payload (GFP)" has been presented in [5-6]. In the functional block diagram of the Generic Flexible Payload (GFP) architecture [5-6], flexibility has been presented in the receive section but in the transmit section, broadband Linearized Travelling Wave Tube Amplifiers (LTWTAs) have been proposed. [7-8] states, "Still challenges remain in the transmit section like filters and power amplifiers". Microwave Power Amplifiers (MPA, either SSPAs or TWTAs) are the major contributor amongst all sub-systems either for space or ground determining the cost of the satellite so it is necessary to make them flexible to improve their performance.

With the development of wide band gap Gallium Nitride (GaN) HFETs devices based SSPAs it has now become possible to replace the TWTAs which will result in saving of mass and volume and hence increased fuel capacity and life of the satellite.

2.1 Need for flexibility (Limitations of fixed payloads)

Most of the satellites launched so far have fixed coverage, fixed link parameters (e.g. transmit EIRP, Surface Flux Density and receive G/T) and fixed frequency of operation so it is difficult to change the important parameters like output power, frequency of operation, bandwidth, coverage, etc. once the satellite is launched. Due to this reason, it is not possible to relocate the satellite, redistribute the power among the beams, switch over to new frequency and also not possible to modify the link parameters (e.g. improve the EIRP in case of fading due to weather especially for satellites operating at higher frequencies). Due to such rigid nature of the transponder, the penalty is paid in terms of the higher DC power generation on-board, higher weight and higher launch cost. Amongst of all sub-systems, the MPAs are the major contributor determining these parameters and are considered the most critical sub-systems either for space or ground. Following are the important parameters of the satellite determined by the MPAs.

(1) Over all DC Power requirement budget (PA being the highest more than 80 % power consumer)
(2) Over all weight budget (Highest weight consumer)
(3) Over all thermal management (PA being the highest power dissipating element)
(4) Overall linearity of system (PA operated in non-linear region)
(5) Overall reliability (life) of the transmitter

Hence, more efforts are necessary to improve the performance of the MPAs. The following examples show how the present satellite technology is rigid in nature and affect the satellite performance.

(i) The MPAs when operated at back off under the multicarrier operation, which is a usual case, the efficiency degrades. This results in degradation of important parameters like increase of DC power consumption, thermal dissipation, channel temperature etc.

(ii) MPA determines the satellite transmit EIRP which decreases due to the degradation in the performance of solar arrays, associated electronics, reliability/redundancy issues, atmospheric (rain, fog) attenuation and aging effect. Due to fixed RF output power of MPA, the EIRP cannot be increased.

(iii) The MPAs are designed to cover the maximum bandwidth possible even when the requirement is for narrow band to cater to redundancy as no scheme is possible so far to change the frequency or bandwidth post launch. While designing such wide band amplifier, the gain of the amplifier has to be sacrificed as the gain bandwidth product remains constant. Reduction of gain results in need for higher power device and decrease in efficiency. [ref flexi

(iv) The thermal design of the MPA is also carried out based on the worst case base plate extreme temperature limits which may occur at the end of life. This results in degradation of efficiency as the device channel temperature puts a limit on it's operation at higher efficiency.

(v) The TWTAs have been used so far due to their higher efficiency in spite of their higher weight and size. So it is necessary to replace these TWTAs with SSPAs which will result in saving of weight and size and hence cost.

(vi) Due to fixed coverage antennae, redistribution and reallocation of coverage is not possible.

(vii) The number of the users defined is also fixed which cannot be increased even though the transponders are under-utilized.

All above limitations result in non-optimal performance of the satellite and hence increases the cost. Therefore, research towards improvement of the performance of satellite communication transponder is necessary for the survival of the satellite communications.

A new technique so called flexible payload or adaptive payload had emerged. This new architecture known as of Generic Flexible Payload (GFP) has been proposed which allows to meet various requirements like evolving business and political landscapes, the emergence of new technologies and applications, or even a change of orbital location or owner [9-10]. The adaptive or flexible payload allows the user to redefine the frequency plan, redistribute the transmit power between service regions and change the EIRP according to the specific need without scarifying the satellite performance. Various techniques have been reported to address above problems which are described in the next section.

2.2 Techniques reported for Making Sub-System Adaptive

The concept of flexible payloads was proposed in early days [9-10] but could be realized very late due to lack of suitable variable components. The idea of intelligent amplifiers seems to be very curious, and changes the way of thinking about RF amplifiers. However, the issue that still has been hard to overcome is the lack of suitable variable components [11]. In order to fulfill the multi-band, multi-mode demands of today's cellular market, current handset implementations are based on parallel line-ups for transmit and receive paths with antenna duplexers and switches to meet the specific requirements of each communication standard. Next-generation wireless systems aim for size and cost reduction by utilizing only one or two adaptive transmit/receive paths to replace the parallel path concept [12]. Although conceptually simple, practical design considerations place severe design constraints and technology challenges on the adaptive circuit blocks required. For most of the circuit functions in the receive path, acceptable implementations have already been demonstrated [13-15]. Adaptive front end receiver is also presented [16] thus it is possible to implement adaptive technique in receive path but major challenges remain, however, in creating the tunable filters and Adaptive Power Amplifiers (APAs) [7-8].

2.3 Work reported so far to address above issues:

Various techniques have been reported to address the limitations described above are listed below.

(a) The efficiency degradation of MPA under back off as listed in (i) can be improved by flexible output power SSPA as reported by [17]

(b) Degradation in the transmit EIRP can be increased by the flexible output power SSPA or flexi TWTA [17].

(c) Adaptive power amplifiers (flexible frequency amplifiers) have been demonstrated in [14-16, 18] using Varactor diodes as switch for various RF applications.

All these works are excellent but they represent only basic concepts and are for ground applications only. They do not give details regarding how the bias to the Varactor can be changed remotely in order to change the capacitance.

(d) The thermal analysis of the SSPA being carried out is for worst case base plate temperature extremes which is non optimal. Real time temperature can be considered for carrying out the thermal analysis and a new technique can be developed which allows to operate the device in single ended configuration until the base plate temperature reaches the specified limit and then switch over to balanced configuration.

(e) TWTAs have long heritage and higher efficiency so consider as the best candidate for payload in spite of their higher weight, volume and cost. This vacuum base technology can be replaced with advanced GaN based SSPAs resulting in reduced weight, volume and cost.

(f) In work [19], it is proposed that power distribution among the beams of an antenna can be done dynamically according to weather prediction information so that the total Number of Non-Served users (NNS) of the satellite network is minimized. The problem of finding the power allocation among the beams of an antenna, aiming that the number of subscribers not receiving the desired quality of service is minimized is also addressed for a satellite communications system with a GEO satellite serving fixed earth terminals. A simple propagation-based algorithm for the dynamic power allocation for multi-beam networks operating at Ka-band and above is presented.

(g) To maximize (increase) the number of the users for the satellite so that cost can per user can be reduced. The problem of maximizing the number of users served has been addressed in [3] and, an improved dynamic power allocation algorithm has been proposed in [4] which can serve even more number of users.

It is clear from the above discussion that the prime objective of reducing cost, can be achieved by improving the efficiency of the MPA through providing flexibility in MPA (SSPA) and by reducing the weight of the satellite through replacement of TWTA by GaN based SSPA.

The following areas have been considered to improve the efficiency and reliability and also to reduce the cost.

(1) Flexible output SSPA

(2) Flexible frequency and bandwidth SSPA

(3) Improving the efficiency of the SSPA by flexible thermal management.

(4) Replacement of TWTAs by GaN based SSPAs

(5) Reliability Improvement of SSPA

2.4 Adaptive Power Amplifiers:

(1) Flexible output SSPA

For every satellite application, the output power requirement changes so every time a new Power Amplifier has to be designed. When operated at back-off for multi-carrier operation, the efficiency of the amplifier reduces. [20]

The prime requirement to make the output power flexible is to change the biasing voltage of the amplifying device. This function is carried out by EPC and such work has been presented in [21]. The author has discussed about design methodology and implementation of a digitally controlled, synchronous gate driven and flexible EPC (Electronic Power Conditioner) with incorporation of an FPGA as its controller, Zero Voltage Switching (ZVS) Technique and synchronous rectification. This EPC offers flexibility in its output load voltages.

(2) Flexible frequency and bandwidth SSPA

The frequency of the amplifier designed is fixed so in future it is not possible to change the frequency if the need arises to change the frequency. Because of this limitation, it is not possible to cater to the requirements like evolving business and political landscapes, the emergence of new technologies and applications, or even a change of orbital location or owner. [22] As the space segment performance is fixed for satellite useful life of 15 years, the users cannot be satisfied with existing satellite onboard or has to wait for new satellite to be launched.

To provide redundancy in the transmit section of the payload, wide band amplifiers are used even though the bandwidth requirement is for narrow band resulting in reduction of gain and efficiency.

To overcome such problems, it is essential to make the sub-systems agile or adaptive. Research towards the program of the Generic Flexible Payload (GFP) was undertaken between the European Space Agency (ESA) and Astrium to satisfy such demand of flexibility [22].

Darbandi [23] has presented Flexible S-band SSPA for Space Application which provides flexibility in terms of output power. As compared to the classical SSPA, the flexible SSPA has 7% improvement in efficiency as 3 dB back off. This work does not give any detail regarding the design concepts, methodology adopted in RF and EPC (Electronic Power Conditioner) and the output power is only up to 20 Watt at S-Band. To adjust the gain change due to change in output power, an additional circuit has been provided which increases the complexity of the circuit. Moreover, no details regarding use of space qualified components are given.

The concept of adaptive power amplifier operating over 1.8 GHz to 4.0 GHz using GaN has been presented by Dawid Rosolowski [24]. The flexibility is achieved by switchable components such as PIN diodes. The work is good work for ground use and do not describe how the switching can be performed and at how accurately the frequency can be changed. When used for space program, the command has to be executed from ground which needs special technique, which is not presented in this work. The components used for space segment must be of space qualified and radiation hardened, such details are not given in this literature.

Similar work is also done on TWTA to provide flexibility by Cuignet [25]. The author has presented very High Efficiency Dual Flexible TWTA, a flexible concept allowing dealing with performances and schedule constraints of Telecommunication Payloads.

(3) Improving the efficiency of the SSPA by flexible thermal management.

As the RF output power requirement increases, the solid state device's operation is limited by its channel or junction temperature. So far the satellite thermal management has been carried out using the worst case temperature of the satellite base plate. The reason for such assumption is that the thermal coating material used to maintain the satellite base plate temperature within the specified limit of -10˚C to +60˚Cdegrade due to ionic radiation and aging. Therefore, the devices are used in balanced configuration to maintain the channel temperature of GaAs FET below 110˚C and of GaN below 160˚C as per the de-rating guidelines [26-27]. The similar concept can be applied to the temperature compensation of the SSPA so that the compensation can be made adaptive to improve the variation of output power and gain over the specified temperature limit resulting in improvement in efficiency.

(4) Replacement of TWTAs by GaN based SSPAs

TWTA versus SSPA

Communications satellite technologies are evolving to meet growing demands for high-rate data, video, and multimedia content distribution. To enable satellites to provide higher bandwidth and data rates, higher power and more efficient components that are reduced in size and mass are needed. We know that Radio-frequency (RF) power amplifiers are one of the key components on-board communications satellites because they consume 80–90% of the spacecraft bus power. The two primary amplifier technologies are TWTAs and SSPAs. TWTAs are electron devices that consist of an EPC and a TWT, and are generally more advantageous for higher power and higher frequencies band applications. SSPA use higher power at lower frequency because of at higher frequency thermal effect problem, so we don't go for high power SSPA at higher frequency. TWTAs have been selected so far as HPAs (High Power Amplifiers) due to non-availability of high power SSPAs with comparable performance with TWTA. The SSPAs' current technology uses GaAs semiconductor material devices. However, future technological advancements such as linearization, miniaturization, and the use of different materials such as GaN, have leveled the playing field for SSPAs.

GaN material has higher bandgap energy more than 3.1 eV so provide various advantages like higher efficiency, higher input impedance than GaAs and hence easier matching, higher voltage operation so the EPC design is simpler and the thermal management is good for higher frequency. [28]

Development of GaN SSPA

Nicol [29] has provided an update on comparison between TWTA and SSPA of the Boeing satellite fleet on-orbit reliability. The GaN Based SSPAs have been developed for space program and will be able to replace the TWTAs resulting in saving of mass, size and cost.

Whitney Q [30] has also compared communication satellite power amplifiers, current and future SSPA and TWTA technologies and tried to prove that still TWTAs supersede SSPAs for higher frequencies. But with GaN technology, it is now possible to replace TWTAs by SSPAs up to C-band. R. Giofre and Laura Gonzalez [28] have demonstrated 300 watt GaN SSPA for Positioning System satellite payloads (L Band).

One of the difficulties of applying GaN devices is that their linearity is generally not as well behaved as GaAs devices. Thus the use of linearization is even more important for GaN amplifiers. Allen katz [31], in his work has shown that linearization can be highly effective at improving the linearity and hence the efficiency of UHF GaN PAs. GaN device technologies indicated that at 50 volt GaN FETs would provide better efficiency than GaAs devices currently being used for UHF space SSPAs. This will replace the Si RF MOSFET power device technology and will provide a linear high power output of over 100 watts as well as the best possible efficiency. Single-chip GaN based MMICs have been reported by James Schellenberg [32] operating at frequencies up to 98GHz with output power level typically 1.5 W. By using power combining techniques, the new level performance for SSPAs there has been increased interest in the use of the milli-metre wave (mmW) spectrum for new communications applications. So, new features of W-band amplifier utilizing a new broad band GaN power MMIC, this amplifier establishes new levels of performance for SSPAs with an average output power of 37 W CW across the full 75 to 100 GHz (28.6%) bandwidth. The SSPA has been tested using water cooling and wind tunnel cooling. These results demonstrate the ability of GaN technology to produce broad band, high-power amplifier operating at millimeter-wave frequencies. The TWTAs' development could not reach up to this frequency level so this development will find no competitor. The development is only for ground application so it needs some more work to be done for space program.

REFERENCES:

[1] C. I. Kourogiorgas, P. D. Arapoglou and A. D. Panagopoulos, "Statistical Characterization of Adjacent Satellite Interference for Earth Stations on Mobile Platforms Operating at Ku and Ka Bands," in IEEE Wireless Communications Letters, vol. 4, no. 1, pp. 82-85, Feb. 2015.doi: 10.1109/LWC.2014.2374177

[2] S. C. Ekpo and D. George, "Impact of Noise Figure on a Satellite Link Performance," in IEEE Communications Letters, vol. 15, no. 9, pp. 977-979, September 2011. doi: 10.1109/LCOMM.2011.072011.111073

[3] A. Destounis and A. D. Panagopoulos, "Dynamic Power Allocation for Broadband Multi-Beam Satellite Communication Networks," in IEEE Communications Letters, vol. 15, no. 4, pp. 380-382, April 2011. doi: 10.1109/LCOMM.2011.020111.102201

[4] N. K. Srivastava and A. K. Chaturvedi, "Flexible and Dynamic Power Allocation in Broadband Multi-Beam Satellites," in IEEE Communications Letters, vol. 17, no. 9, pp. 1722-1725, September 2013.doi: 10.1109/LCOMM.2013.080113.130615

[5] Agile Equipment for an Advanced Ku/Ka Satellite. ESA Workshop on Advanced Flexible Telecom Payloads 18-20 November 2008 at ESTEC.

[6] An Overview of the Generic Flexible Payload Program and Future Technologies for Optimizing Payloads to Business Needs 2nd ESA Workshop on Advanced Flexible Telecom Payloads (17-19 April 2012, ESA-ESTEC, Noordwijk – The Netherlands).

[7] D. Qiao, R. Molfino, S. M. Lardizabal, B. Pillans, P. M. Asbeck, and G. Jerinic, "An intelligently controlled RF power amplifier with a reconfigurable MEMS-varactor tuner," *IEEE Trans. Microw. Theory Tech.*, vol. 53, no. 3, pp. 1089–1095, Mar. 2005.

[8] T. J. Hyeong, S. L. Hyun, S. C. Ik, and D. K. Chul, "Efficiency enhancement method for high-power amplifiers using a dynamic load adaptation technique," in *Proc. IEEE MTTS Int. Microwave Symposium.*, 2005, pp. 2059–2062

[9] Perotta, G.; Rispoli, F.; Bardelli, L., "Flexible payloads for business oriented communication satellites: The European scenario," in Electro Technical Conference, 1989. Proceedings. 'Integrating Research, Industry and Education in Energy and Communication Engineering', MELECON '89, Mediterranean, vol., no., pp.480-484, 11-13 Apr 1989.

[10] Flexible payloads for telecommunication satellites - a Thales perspective Nathalie Font, Cyrille Blosse, Patrick Lautier, Arnaud Barthère, and Philippe Voisin 32nd AIAA International Communications Satellite Systems Conference. SPACE Conferences and Exposition, (AIAA 2014-4382).

[11] Rosolowski, D.W.; Wojtasiak, W.; Gryglewski, D., "A 27 dBm microwave amplifier with varactors-controlled matching networks," in Microwave Radar and Wireless Communications (MIKON), 2010 18th International Conference on, vol., no., pp.1-4, 14-16 June 20

[12] W. C. Edmund Neo, Yu Lin, Xiao-dong Liu, Leo C. N. de Vreede, Lawrence E. Larson, Marco Spirito, Marco J. Pelk, Koen Buisman, Atef Akhnoukh, Anton de Graauw, and Lis K. Nanver, *Adaptive Multi-Band Multi-Mode Power Amplifier Using Integrated Varactor-Based Tunable Matching Networks,* in proc. IEEE journal of solid-state circuits, Vol. 41, No. 9, September 2006.

[13] J. Ryynanen, K. Kivekas, J. Jussila, A. Parssinen, and K. Halonen, “A dual-band RF front-end for WCDMA and GSM applications,” in *Proc. IEEE Custom Integrated Circuits Conf.*, 2000, pp. 175–178.

[14] D. Wang, X. Wang, A. Eshraghi, D. Chang, and P. Bacon, “A fully integrated GSM/DCS/PCS Rx VCO with fast switching auto-band selection,” in *Proc. IEEE Radio and Wireless Conf.*, 2002, pp. 209–212.

[15] A. Tasic, W. A. Serdijn, and J. R. Long, “Multi-standard/multi-band adaptive voltage-controlled oscillator,” in *Proc. IEEE Radio Frequency Integrated Circuits Symp.*, 2004, pp. 135–138

[16] A. Tasic, S. T. Lim, W. A. Serdijn and J. R. Long, "Design of Adaptive Multimode RF Front-End Circuits," in IEEE Journal of Solid-State Circuits, vol. 42, no. 2, pp. 313-322, Feb. 2007.doi: 10.1109/JSSC.2006.889387

[17] R J Doshi, Deepak Ghodgaonkar, D K Singh, D K Das, “Flexible Solid State Power Amplifier for Space use.” International Journal of Microwave and Optical Technology, Vol.10, No.2, pp126-131 March 2015

[18] D. Rosolowski, W. Wojtasiak and T. Morawski,"A S-band 7 W GaN HEMT adaptive power amplifier," 2012 19th International Conference on Microwaves, Radar & Wireless Communications, Warsaw, 2012, pp. 304-307.doi: 10.1109/MIKON.2012

[19] A. Destounis and A. D. Panagopoulos, "Dynamic Power Allocation for Broadband Multi-Beam Satellite Communication Networks," in IEEE Communications Letters, vol. 15, no. 4, pp. 380-382, April 2011.doi: 10.1109/LCOMM.2011.020111.102201

[20] B.D. Geller, F.T. Assal, R.K. Gupta and P.K. Cline, “A technique for the maintenance of FET power amplifier efficiency under back-off,” IEEE MTT-S Int. Microwave Spp. Dig., 1989, pp. 949-952.

[21] Avi Vyas, Amit Kumar, Trapti Katiyar, J P Joshi, Dinesh Singh, Pratik Jain, Himanshu Shah, “Digitally Controlled Flexible EPC for SSPA”*2015 IEEE International Transportation Electrification Conference (ITEC)*, Chennai, 2015, pp. 1-7.doi: 10.1109/ITEC-India.2015.7386888

[22] An Overview of the Generic Flexible Payload Program and Future Technologies for Optimizing Payloads to Business Needs 2nd ESA Workshop on Advanced Flexible Telecom Payloads (17-19 April 2012, ESA-ESTEC, Noordwijk – The Netherlands).

[23] A. Darbandi, M. Zoyo, J. Y. Touchais and Y. Butel, "Flexible S-band SSPA for Space Application," *2008 NASA/ESA Conference on Adaptive Hardware and Systems*, Noordwijk, 2008, pp. 70-76.doi: 10.1109/AHS.2008.47

[24] D. Rosolowski, W. Wojtasiak and T. Morawski,"A S-band 7 W GaN HEMT adaptive power amplifier," *2012 19th International Conference on Microwaves, Radar & Wireless Communications*, Warsaw, 2012, pp. 304-307.doi: 10.1109/MIKON.2012

[25] E. Cuignet, E. Tonello, J. Maynard and P. Boone, "Very High Efficiency Dual Flexible TWTA, a flexible concept allowing to deal with performances and schedule constraints of Telecommunication Payloads," *2013 IEEE 14th International Vacuum Electronics Conference (IVEC)*, Paris, 2013, pp. 1-2.doi: 10.1109/IVEC.2013.6570951

[26] JPL De-rating GuidelinesJPL-D-8545 Revision D, Jet Propulsion Laboratory under contract to National Aeronautics and Space Administration (NASA), pp 14-15 (2003)

[27] Space product Assurance, De-rating-EEE components, ECSS-Q-ST-30-11C Rev1, 4 October, 2011

[28] R. Giofre, P. Colantonio, L. Gonzalez, L. Cabria and F. De Arriba, “A 300W complete GaN solid state power amplifier for positioning system satellite payload,”2016 IEEE MIT-S International Microwave Symposium(IMS),San Francisco, CA,2016,pp.1-3.Doi:10.1109/MWSYM.2016,7540096

[29] E. F. Nicol, B. J. Mangus, J. R. Grebliunas, K. Woolrich and J. R. Schirmer, "TWTA versus SSPA: A comparison update of the Boeing satellite fleet on-orbit reliability," *2013 IEEE 14th International Vacuum Electronics Conference (IVEC)*, Paris, 2013, pp. 1-2.doi: 10.1109 /IVEC .2013.6571087

[30] Whitney Q, Raichelle J, and Kerri L, "Communication satellite power amplifiers: current and future SSPA and TWTA technologies" International Journal of Satellite Communications and Networking. Volume 34, Issue 2, pages 95–113, March/April 2016 DOI: 10.1002/sat.10

[31] A. Katz, B. Eggleston, D. McGee and J. MacDonald, "UHF GaN SSPA for Space Applications," *2010 IEEE Radio and Wireless Symposium (RWS)*, New Orleans, LA, 2010, pp. 108-111. doi: 10.1109/RWS.2010.5434222

[32] J. Schellenberg, A. Tran, Lani Bui, A. Cuevas and E. Watkins, "37 W, 75–100 GHz GaN power amplifier," *2016 IEEE MTT-S International Microwave Symposium (IMS)*, San Francisco, CA, 2016, pp. 1-4. doi: 10.1109/MWSYM.2016.

CHAPTER 3
Efficiency Improvement Using Flexible Output SSPA for Space Use

3.1 Objective:

The SSPAs used so far in satellite communication are with fixed output power with efficiency of the order of 30% at specified output power (fixed). But when operated at back-off, the efficiency reduces to around 20 % so a large amount of DC power is wasted as a heat leading to degrade thermal management.

Depending upon coverage area and user requirement, the power amplifier is selected for satellite transponder design. A common practice is to design a payload with state-of-the-art sub-systems available in the market. For example, 100 watt SSPAs for UHF-band, 40 watt SSPAs for L-band and 15 watt SSPAs for C-band are available off-the-shelf with space heritage design. They are commonly selected for satellite transponder design. Anything different from the off-the-shelf space heritage product needs new design and new qualification leads to impact on cost and schedule.

The following examples show the applications where flexible output power SSPAs are needed.

(i) Depending upon the output power requirement, SSPAs with different output power are designed.

(ii) The Direct to Home (DTH) Television reception is highly distorted and sometimes the Television reception is fully lost due to rain fading of the signal (especially when the communication is at Ku and Ka Band).

(iii) Similarly in the low traffic regions such as above sea or low populated areas and multi-carrier operations the SSPAs are operated at back-off.

In all these applications, the efficiency is very low at back-off. Suppose in future, there is a requirement of higher output power from the payload, one cannot increase the power by any means in the so far designed SSPAs.

20 watt GaAs SSPA				200 watt GaN SSPA			
RF Input level	P_{out} (dBm)	DC power consumption (watt)	η_{add} (%)	RF Input level	P_{out} (dBm)	DC power consumption (watt)	η_{add} (%)
Nominal	20	54	37	Nominal	200	327	58
Pin-4	10	42	23	Pin-4	100	263	48
Pin-7	5	37	13	Pin-7	50	150	30

Table 3.1.1 SSPA Efficiency under Back - off

Table 3.1.1 shows the relationship between the input back-off with the DC power consumption and Power Added Efficiency (PAE, η_{add}) of 20 Watt GaAs FET SSPA developed for space applications. DC power consumption does not reduce at the same rate as output power. So efficiency reduces drastically at every 3 dB output power back-off. To improve the efficiency under back-off condition the DC power consumption has to be reduced. This leads to need for Flexible output power SSPA.

Target Specifications of Flexible output power SSPA:

Parameter	20 watt GaAs FET SSPA	200 watt GaN HFET SSPA
Frequency	3700-3900 MHz	1250-1350 MHz
Gain @ 2 dB GCP	12 dB	14 dB
P_{out}	40 dBm (10 watt)	53 dBm (200 watt)
PAE at nominal Pout	40 %	55 %
Improvement in PAE at 3 dB B/O	5 %	5 %

Table 3.1.2 Targeted Specifications of flexible output power SSPA

Two types of the SSPAs were designed for demonstration of this concept. Initially the SSPA was designed using Gallium Arsenide (GaAs) MESFET device delivering 20 Watt RF output power and later another amplifier was designed using state of the art technology Gallium Nitride (GaN) HFET device delivering 200 watt RF output power. The power added efficiency degradation at 3 dB output back off was of the order of 14 % and 10 % for 20 Watt and 200 Watt device respectively. Based on the theoretical analysis, the target specification for efficiency improvement was set for 5 % at 3 dB back off. Table 4.1.2 gives the detail of major targeted specifications of 20 Watt as well as 200 Watt SSPAs.

3.2 Theoretical Background:

The different classes of operation of amplifiers are A, B, AB, C, D, E and F. For satellite applications class AB is preferred for optimum performance in terms of better linearity and efficiency. The following explanation demonstrates the relation of the efficiency at saturation and at back off for fixed drain voltage. [1]

Under ideal fixed voltage class B operation, the DC input power or DC power consumption (P_{dc}), defined by product of drain current (I_{ds}) and drain voltage (V_{ds}) is a function of the drain current amplitude and the drain current amplitude and the drain voltage is given by

$$P_{DC} = \frac{\Delta I}{\pi} \cdot V_D \qquad (1)$$

The RF output power is given by

$$P_{out} = \frac{R_L . \Delta I^2}{8} \qquad (2)$$

Where R_L is the class B load resistance at any given drive level an optimal drain voltage exists that maximizes the output power, such that

$$V_D = \sqrt{2 \cdot R_L \cdot P_{out}} + V_k \qquad (3)$$

Where V_K is the knee voltage. The Knee Voltage is not the fixed value commonly determined from a curve tracer measurement.

From Equation (1), (2) & (3), the drain efficiency of the ideal class B amplifier under Back-off, with fixed drain bias becomes

$$\eta_d^{fixed} = \frac{\pi}{4} \cdot \left(\frac{1-\alpha}{1+\alpha} \right) \cdot \sqrt{\beta} \qquad (4)$$

Where $\alpha = \frac{V_k}{V_{bk} - V_{po}}$ and represents the FET "ideally factor" and β= Pout/Pout max, the back-off ratio.

For the same amplifier with optimal variable drain bias,

$$\eta_d^{\text{var}} = \frac{\pi}{4} \cdot \frac{1}{1 + \frac{2\alpha}{(1-\alpha) \cdot \sqrt{\beta}}} \qquad (5)$$

The ratio of drain efficiency of the two operating modes is now given by

$$\frac{\eta_d^{Var}}{\eta_d^{fixed}} = \frac{1+\alpha}{(1-\alpha)\cdot\sqrt{\beta}+2\alpha} \quad (6)$$

For an ideal device (α =0), the ratio is always greater than 1 indicating higher efficiency under "extended saturation" operation. Thus above discussion shows that the SSPA offers higher efficiency at saturation as compared to the back-off condition. The amount of saturation is defined by the term Gain Compression which is an amount of the gain reduction from the back-off to nominal operating condition. Thus the efficiency at back off is lower as compared to the saturation. [2-5]

The DC power consumption of the devices can be changed by either changing the Drain voltage V_{ds} or by changing the Drain Current I_{ds}. The drain current can be changed by changing gate-to source voltage V_{gs}. Changing the gate voltage changes the gain of the amplifier which needs additional gain adjustment circuit which is not advisable for space hardware. Hence, drain voltage is varied in most cases which require critical design challenges to ensure the amplifier's unconditional stability. The Electronic Power Conditioner (EPC) has been designed according to the required drain voltages which is described in [6-7]. In the successive section, high power amplifier has been described in detail using Automated Design Software (ADS).

3.3 Design, Optimization and Simulation

In order to demonstrate the concept, two types of the devices (1) GaAs MESFET (2) GaN HEMT were selected for designs. Out of these two, design of a high power amplifier using GaN HEMT has been presented here whereas only results of GaAs MESFET amplifier are listed.

The concept of flexible output power SSPA has been demonstrated in the following steps.

(1) Selection of Power device (GaN, GaAs or MOSFET)

(2) Design of an amplifier with conjugate match and load pull match using Harmonic Balance

(3) Characterization of amplifier under for dynamic biasing

(4) Collection of data (look up table) for programming into storage device

(5) Testing and results

For Power amplifiers, GaAs semi-conductor materials were widely used so far but due to lower band gap energy, they could not be operated beyond 9 volts. Hence many of them were used in parallel to get higher power resulting in lower efficiency.

Si based RF MOSFETs were also used for power amplifications as they could be operated at 28 volts but due to limitations of Si, they could not be used beyond 2 GHz.

This called for innovation of a newer material with wider bandgap energy which can be operated at higher frequencies.

With innovations of Gallium Nitride (GaN) semiconductor, it has now become possible to design and develop high power amplifier with excellent performance.

3.4 Power Amplifier Design using GaN:

The active device used in this amplifier is 180W Gallium Nitride based High Electron Mobility GaN-HEMT Transistor from Cree (CGH40180), a large signal model and has following features.

- 28 V to 32 V Operation
- Up to 2.4 GHz operation availability
- Small signal gain of 16 dB at 2.0 GHz
- Saturated Power of 180 W and 60 % Efficiency at this level

Thanks to wide bandgap of GaN, power density of the material is 10 to 20 times higher than GaAs-based devices. Hence the GaN components are much smaller and exhibiting low capacitance characteristics.

The Amplifier is designed with the help of non-linear model of the device on Advanced Design Software (ADS) platform. The following steps were performed but only load pull design is explained in detail.

1. Biasing the device
2. Stability Analysis
3. Selection of Load and Source Impedances
4. Design of matching network to check performance of device when it is conjugate matched
5. Using Load Pull Technique to find the optimum load impedance.
6. Design of Matching Network after finding the optimum load impedances.
7. Combining the two sides of the Amplifier.
8. Fabrication and measurement.
9. Practically measured results.

3.5 Finding optimum impedance through Load Pull

In the load-pull measurement, the performance of the device is tracked through varying source and/or load impedances. Impedance values are varied by the means of either manual or automatic tuners which are controlled by a computer. The computer then fits the measured performance parameters on a gamma source or gamma load plane. Appropriate impedances for source and load are then determined so that the matching networks can be designed. In this project the load pull measurements were carried out by using the design guide given in the ADS 2008 with the help of the nonlinear model.

Load pull simulations can be done in ADS using HB1Tone_LoadPull design guide with a large-signal/non-linear model of transistor. For this work, a large signal model of 120 watt GaN HFET is used. This device is used for the load pull analysis as this device has the same characteristics as that of 200 watt GaN HFET, the only difference is that two 120 watt devices are combined to make 200 watt device. Fig 3.5.1 shows the simulation setup from this design guide and resulting load-pull contours for output power and PAE as a function of load impedance. Figure 3.5.2 shows the chart for the process of this harmonic balance simulation.

In Fig 3.5.3 each contours indicates the set of impedances corresponding to a constant output power or PAE.

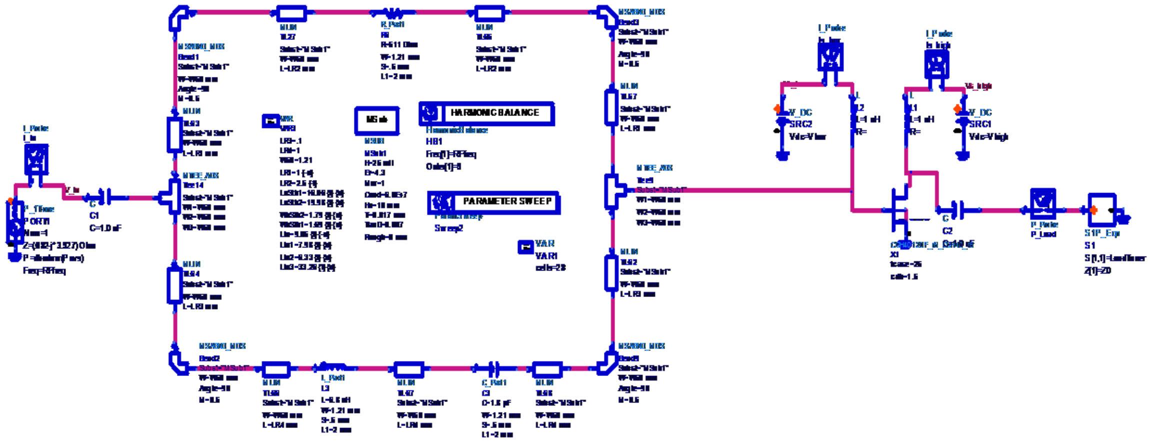


Fig 3.5.1: Setup for Load Pull Analysis

The below load-pull circuit uses harmonic balance simulation in ADS. This iterative simulation calculates the response of large signal circuits driven by either single or multiple sources and tries to find a stationary solution for the non-linear system in the frequency domain.

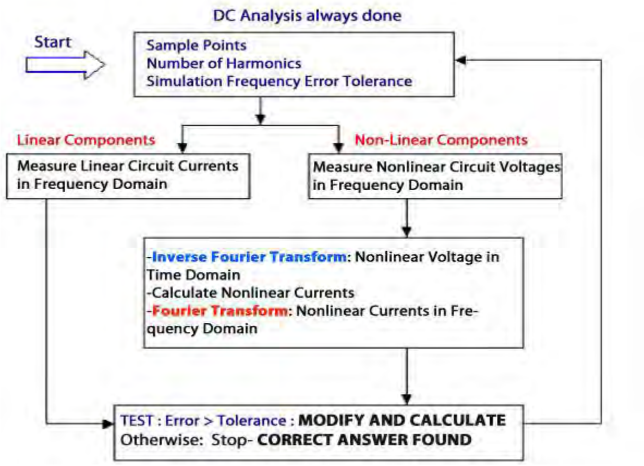


Fig 3.5.2 Flow Chart of Harmonic Balance Simulation

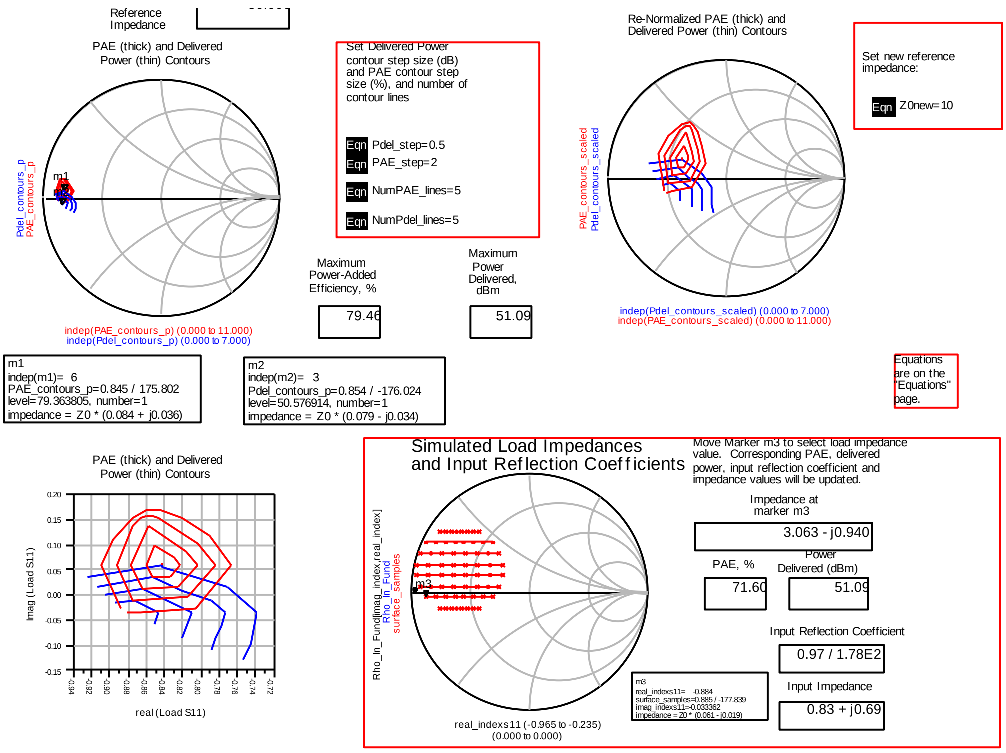


Fig 3.5.3 Resulting PAE and delivered power contours drawn in Smith Chart

Fig 3.5.4 shows the output power from the power match condition at 2dB compression point obtained through the load pull technique. The impedence was found to be (3.063 – j*0.940) Ω. The matching network was designed to transform the source and load impedance to the 50Ω line using Smith chart, were found to be (1.058 – j*3.454) Ω and (3.063 – j*0.940) Ω respectively.

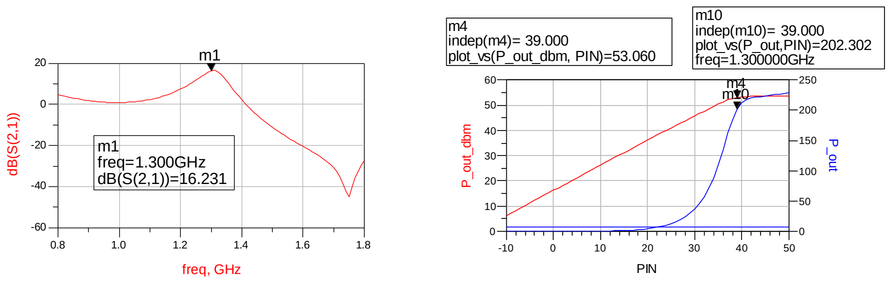


Fig 3.5.4: Gain & Output Power for power matched amplifier

3.6 Combining the two sides of the amplifier:

The two sides of the amplifier can be combined either by using the Wilkinson power divider. The two input sides are fed power in phase through a 3dB equal power divider & the output power from the two output sides are combined with the help of the combiner that was matched to the 50Ω line. The gain was found satisfactory however the input return loss was not good. In order to improve the return loss extra 90^0 line was added to the input and the output to make the amplifier work in the balanced configuration. The Electromagnetic-Circuit co-simulation feature enables to combine EM and circuit simulations from the schematic.

After this configuration the output power achieved at 1dB and 2dB compression point as shown in fig 3.6.1 by markers (m5 & m6) and (m51 & m53) respectively. At one 1dB compress the output power is 51.957 dBm (156W) however at 2dB compression point we are able to achieve 53.0 dBm (199.897W) which is close to 200Watts.Fig 3.6.2 shows the large signal gain at 1dB and 2 dB Compression points. The amplifier has a flat gain for small signals and decreases as the compression is increased.

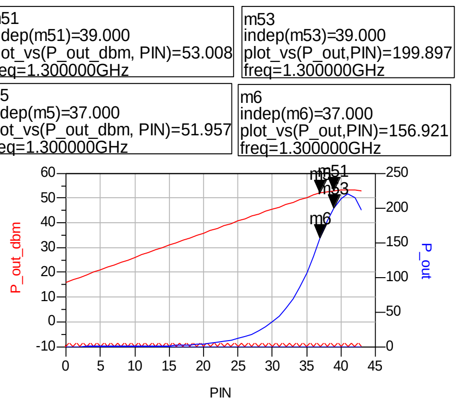


Fig.3.6.1: Plot of Output Power

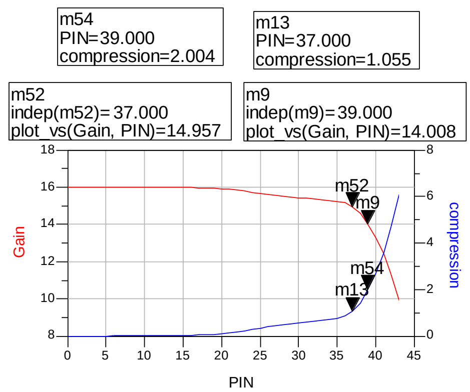


Fig.3.6.2: Gain & Compression

(i) Power Added Efficiency (PAE):

Fig 3.6.3 gives the PAE at 1dB& 2dB compression point which clearly shows the improvement in the power added efficiency from 52.7% to 58.4% as one move into compression. It shows that the PAE increases as the input power increases then reaches at the peak point and then degrades when further the input power is increased which is obvious because at the saturation the output power will not increase but the D.C power and the applied input power will keep on increasing.

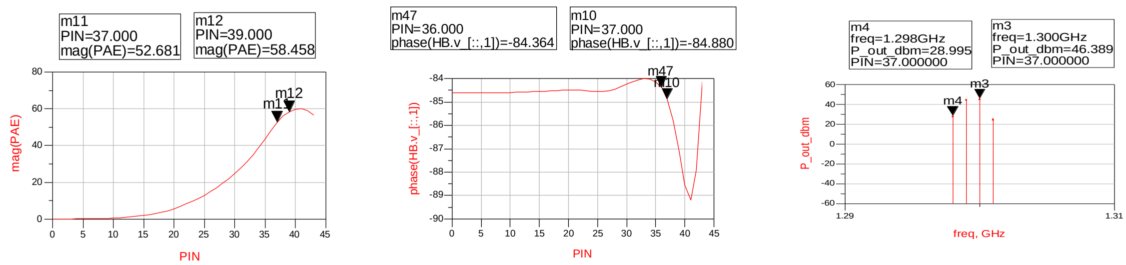


Fig. 3.6.3 PAE, AM-PM Conversion and IMD at 1dB and 2 dB Compression point.

(ii) AM-PM Conversion and Tone IMD Test:

Another parameter of interest is AM/PM conversion, which is a prime factor in determining Bit Error Rate (BER). Ideally output phase should be independent of input power. But, as device is operated in non-linear region, output phase changes with change in input power. From the above Fig.3.6.3 it follows that the AM-PM Conversion is 0.516^{0}/dB at 1 dB compression. As shows the 3rd order Inter Modulation Products (IMD) for 1dB compression point at very closely spaced frequencies which are 1.3GHz & 1.299GHz.

3.7 ADS Layout

After obtaining the simulation results the input and the layout of the input and output matching networks were realized in the ADS. Layout of the high power stage is shown below in Fig. 3.8.

3.8 Fabrication:

The layout was exported as Gerber files from ADS and it was milled on a printed circuit board known as PCB. The test box was prepared so that the device can be mounted properly and the heat generated can be dissipated fast.

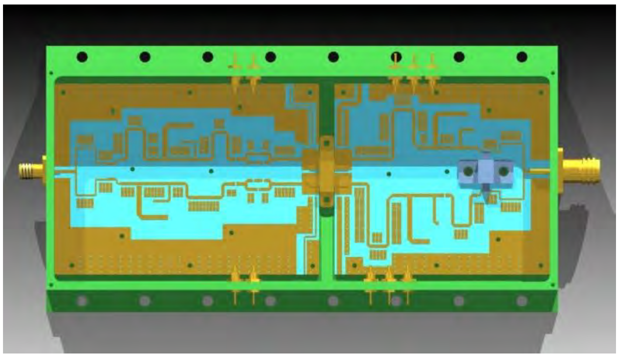


Fig.3.8 Layout of the Power Amplifier

3.9 Measured results:

The response of the amplifier was measured with the help of PNA-X and was found to be closely matching with the simulated values. The amplifier was tested for different drain voltage and different gain settings to collect the data to store in EEPROM controller. The results are mentioned in the following tables in the next section. Important observations are as follows.

When the device is operated at back-off, it suffers from the following disadvantages.

- Efficiency of the device is decreasing.
- Chanel temperature is increasing that is affecting the reliability of the device
- The device gain has increased that affects the overall system gain.
- The device has come out of the compression, making the output of the amplifier change with the slight change in the input applied to the amplifier.

So in order to improve the performance of the device simultaneously not affecting the overall system gain of the amplifier the device again needs to be operated at the compression. This can either be done either by reducing the device bias voltage either the drain voltage or the gate voltage.

By reducing the bias voltage, following advantages are obtained:

- Power dissipation has reduced which in turn has resulted in the improvement of the device channel temperature.

- As the channel temperature has decreased, it means that the reliability of the device has improved.
- The gain of the amplifier is constant, so the overall system gain is same even at the back-off.
- The device is again running in the compression so the fluctuation is the output power is less with the fluctuation in the input drive level.

3.10 Dynamic (Adaptive) Bias approach:

Some sort of controller is required which will vary the drain voltage in accordance with input power back-off. This has been realized as follows.

The RF input power was monitored using a coupler and this coupled power was converted into DC voltage using RF detector. This detected signal was used for reference signal for the dynamic biasing controller. The dynamic biasing controller consists of A/D converters, PROMs, a PROM controller and D/A converters, which provide control voltage for drain.

The block diagram of SSPA with Dynamic Bias approach is shown in Fig 3.10.

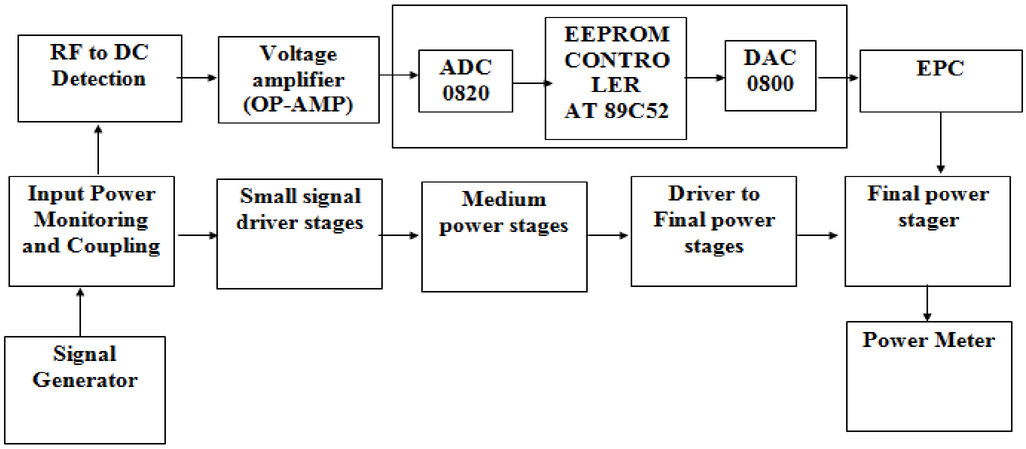


Fig.3.10: Block diagram of SSPA with dynamic bias approach

3.11 Realization and testing of Amplifier with EEPROM controller

As compared to the ground application, selection of the components with space qualification and Radiation Hardening (Rad-Hard) is critical and hence very limited choice is available. Two types of amplifiers (1) 20 watt GaAs MESFET amplifier and (2) 200 watt GaN HFET amplifier were tested and results are presented below. Table 3.11.1 presents look up table required to be burn-in into the EEPROM controller for different RF input drive levels for 20-watt amplifier and Table 3.11.2 presents the DC power consumption and efficiency improvement for different drive levels.

Output of ADC (volt)	Input to DAC (volt)	RF Input power level
4	9.0	Nominal RF input
3.5	7.73	1 dB input back-off
3.0	6.96	2 dB input back-off
2.5	6.25	3 dB input back-off
2.0	5.74	4 dB input back-off
1.5	5.40	5 dB input back-off

Table 3.11.1 Typical look up table for 20 watt GaAs MESFET amplifier (for EEPROM controller).

Pin (dBm)	Efficiency improvement (%)	DC power improvement (watt)
18 (Nominal)	0	0
17	1.49	2.19
16	5.19	4.64
15	6.91	5.52
14	6.80	5.66
13	6.22	5.63

Table 3.11.2 Improvement in Efficiency and power consumption for 20-watt device

The DC power saving of about 5 Watt at 3 dB input back-off (7 % efficiency improvement) for 20 watt SSPA is quite considerable for on-board applications.

Similar concept when applied to higher power SSPA where the drain voltage of the driver stage of the final stage can also be varied in addition to that of final device, the improvement number is of the order is 10 %.

The GaN amplifier (200 watt) designed above was tested and the amount of DC power saving is shown in the following Tables 3.11.3 and 3.11.4.

P_{in} (dBm)	P_{out} (dBm)	IRF (Amp)	VDC (volt)	P_{dc} (watt)	P_{out} (watt)	η(%)
39	53.0	11.7	28	327.6	200	58.5
38	52.6	11.1	28	310.8	182	56.3
37	52.0	10.3	28	288.4	156	52.7
36	51.2	9.4	28	263.2	132	48.2

Table 3.11.3 Test data for 200 watt GaN Device without dynamic bias

P_{in} (dBm)	P_{out} (dBm)	IRF (Amp)	VDC (volt)	P_{dc} (watt)	P_{out} (watt)	η(%)
39	53.0	11.7	28	327.6	200	58.5
38	52.6	10.4	25.2	262.1	156	57.8
37	52.0	9.3	22.9	213.0	126	56.7
36	51.2	8.3	21	174.3	100	55

Table 3.11.4 Test data for 200 watt GaN Device with dynamic bias

As seen from above tables, for a single stage high power amplifier the efficiency improvement is about 7 % for 3 dB output back-off. When the same concept is applied to its driver stage (in this case it is 20 Watt device), additional improvement of the order of 3 % is achieved resulting an overall improvement of 10 % at 3 dB back off. This will allow the SSPA designer to compete the TWTA in terms of efficiency in addition to mass, volume and cost and replace the TWTAs.

Comparison between targeted and achieved performance with dynamic biasing:

Parameter	Target Specifications	Achieved performance
Frequency	3700-3900 MHz	3700-3900 MHz
Gain @ 2 dB GCP	12 dB	12 dB
P_{out}	40 dBm (10 watt)	40 dBm (10 watt)
PAE at nominal Pout	40 %	42 %
Improvement in PAE at 3 dB B/O	5 %	7 %

Table 3.11.5 Targeted versus achieved performance for 20 watt GaAs Device with dynamic bias

Parameter	Target Specifications	Achieved performance
Frequency	1250-1350 MHz	1250-1350 MHz
Gain @ 2 dB GCP	14 dB	14 dB
P_{out}	53 dBm (200 watt)	53 dBm (200 watt)
PAE at nominal Pout	50 %	58 %
Improvement in PAE at 3 dB B/O	5 %	7 %

Table 3.11.6 Targeted versus achieved performance for 200 watt GaN Device with dynamic bias

The above Tables 3.11.5 and 3.11.6 compare the achieved performance with the targeted specifications and can be seen from the tables that the achieved performance is better than the expected for efficiency improvement at 3 dB back off.

Similar work, “Flexible S-Band SSPAs for Space Applications” has been reported by A. Darbandi. In this work only conceptual block schematic and measured results are presented but do not give any design detail regarding the technique by which the flexibility is achieved. The reported improvement in efficiency is 7 % whereas in present case, the improvement is 7 % only for the final stage, which is 10 % when the same technique is applied to it’s driver stage.

3.12 Conclusion

The concept of the flexible output power SSPA has been demonstrated using GaAs and GaN devices with hardware realization for on-board space applications. The overall efficiency improvement achieved is 10 % which is higher than the reported number of 7 %. It can be seen from the measured results that a considerable amount of DC power, 5 Watt in 20 watt SSPA and 90 Watt in 200 watt SSPA, at 3dB input back-off can be saved using this approach. This will result in saving of DC power generation on-board and hence the launching cost. Using this SSPA the satellite transmit power can be varied automatically to meet the losses due to atmosphere and rain fading. The reliability of the device also can be improved by reducing its drain voltage and channel temperature. This is considered as a remarkable power saving for space application and also the significant technique to improve the link availability for DTH application. In addition to efficiency improvement, it provides flexibility in terms of output power which will help the satellite users to update themselves with the rapidly changing technology.

REFERENCES:

[1] B.D. Geller, F.T. Assal, R.K. Gupta and P.K. Cline, “A technique for the maintenance of FET power amplifier efficiency under back-off,” IEEE MTT-S Int. Microwave Spp. Dig., 1989, pp. 949-952.

[2] M. Iwamoto, A. Williams, P. F. Chen, A. G. Metzger, L. E. Larson, and P. M. Asbeck, "An extended Doherty amplifier with high efficiency over a wide power range," IEEE Trans. Microwave Theory & Tech., vol. 49, no. 12, pp. 2472-2479, December 2001.

[3] T. Yamamoto, T. Kithara, and S. Hiura, "50% drain efficiency Doherty amplifier with optimized power range for W-CDMA signal," 2007 IEEE MTT-S Int. Microwave Symp. Dig., pp. 1263-1266, June 2007.

[4] M. J. Pelk, W. C. E. Neo, J. R. Gajadharsing, R. S. Pengelly, and L. C. N. de Vreede, "A high-efficiency 100-W GaN three-way Doherty amplifier for base-station applications," IEEE Trans. Microwave Theory & Tech., vol. 56, no. 7, pp. 1582- 1591, July 2008.

[5] D. F. Kimball, J. Jeong, C. Hsia, P. Drexler, S. Lanfranco, W. Nagy, K. Linthicum, L. E. Larson, and P. M. Asbeck, "High efficiency envelope-tracking W -CDMA base-station amplifier using GaN HFETs," IEEE Trans. Microwave Theory & Tech., vol. 54, no. 11, pp. 3848-3856, November 2006.

[6] Keya Shukla, N.V. Bijeev, Virender Kumar, Praveen Bhardhwaj, Amit Bhatt, Ramesh Doshi, “EPC with Dynamic Bias Control for SSPA for Space Applications” International conference on Advances in Power Conversion and Energy Technologies, APCET

[7] Avi Vyas, Amit Kumar, Trapti Katiyar, J P Joshi, Dinesh Singh, Pratik Jain, Himanshu Shah, “Digitally Controlled Flexible EPC for SSPA”*2015* IEEE International Transportation *Electrification Conference* (ITEC), Chennai, 2015, pp. 1-7.doi: 10.1109/ITEC-India.2015.7386888

[8] A. Darbandi, M. Zoyo, J. Y. Touchais and Y. Butel, “Flexible S-band SSPA for Space Application," 2008 NASA/ESA Conference on Adaptive Hardware and Systems, Noordwijk, 2008, pp. 70-76. doi: 10.1109/AHS.2008.47

CHAPTER 4
Adaptive Frequency and Bandwidth SSPA

4.1 Objective:

The Solid State Power Amplifier (SSPA) can be made flexible in terms of frequency using PIN diode and Varactor diode switch to improve the efficiency and thermal performance for space segment of Satellite Communications. The flexibility allows user to keep themselves with the changing scenario of satellite communications. The Gallium Nitride (GaN) based SSPAs using this concept will compete the TWTAs for on-board applications also. It also demonstrates the circuit topology for selecting the required narrow frequency band rather than designing broad band Solid State Power Amplifier resulting in improvement of efficiency and channel temperature. Improvement of channel temperature in space application improves the reliability of active devices.

4.2 Introduction:

As compared to terrestrial gateways, the satellite based solutions are very costly. Moreover, the defined performance is unaltered (fixed) for the proposed satellite life of 10 to 15 years. But as the space segment performance is fixed one cannot be satisfied with existing satellites onboard or has to wait for new satellite to be launched. Thus it is the time to reduce the cost by some means. By increasing the design life, the cost per bit can be reduced but it becomes very difficult for the operator to plan a robust business case over such long period. The concept of flexible payload will be able to keep the satellite user with the changing market trends. [1-3]

Three Axes of Flexibility has been presented in [3]. In the functional block diagram of the Generic Flexible Payload (GFP) architecture, the broadband LTWTAs are presented which may be with an assumption that flexible TWTAs or SSPAs are not available as of now. Flexible output power SSPAs and TWTAs have been developed but Flexible frequency SSPAs and TWTAs for space are not known so far to the best of our knowledge. This is the motivation behind the work towards the flexible frequency SSPAs. Broadband TWTAs are available for higher frequencies (C, Ku and Ka) but at lower frequencies (L1, Ls and S), they are not available. With the availability of Unmatched Gallium Nitride (GaN) HFETs delivering 250 watt RF power and capable of operating from 1 GHz to 2.5 GHz, it is possible to design flexible frequency SSPA covering L1, L5 and S Band to which TWTAs will never compete.

So far efforts have been made to design wide band amplifiers to cover more frequency bands but no such high power amplifier is designed which is switchable between different frequency bands to cover wider band and get the benefit of power efficiency to the best of our knowledge. While designing flexible frequency SSPAs, few more advantages in terms of improvement in efficiency and thermal performance have been achieved. The following section describes the need for flexible frequency SSPAs.

4.2.1 Need for the flexible frequency SSPAs:

This section describes the need for flexibility in terms of frequency for space applications while addressing the advantages of narrow band versus wide band design.

4.2.2 Need for the flexible frequency SSPAs in the Existing satellites applications:

In satellite communications, the wide band signals received by antenna on board are amplified by receiver with minimum insertion of noise, channelized into narrow band channels by filters, amplified to a certain level by amplifiers with minimum insertion of non-linearity and then transmitted by antenna to earth. This channelization is necessary because of the following reasons.

(1) Single amplifier is unable to deliver the required RF power over the wide frequency range (e.g. 15 watts over 300 to 500 MHz at C-band and 100 watts over the wide frequency range of 50 MHz at UHF Band).

(2) Even if such amplifier is available, it is not possible to achieve required linearity with good efficiency.

(3) Moreover it provides redundancy in case of failure of the amplifier (amplifiers are the most likely sub-systems prone to malfunction) and hence improves the overall reliability of the satellite. [4-6]

In order to provide redundancy, the amplifiers have to be designed for wider band, even though the usable bandwidth requirement is low (narrow band). At higher frequencies, due to parasitic effects in the active devices it is very difficult to achieve wider bandwidth. Moreover, while designing such wide band amplifier, the gain of the amplifier has to be sacrificed as the gain bandwidth product remains constant. The SSPAs designed so far for space program have been designed for fixed frequency and fixed bandwidth so the power efficiency has to be sacrificed. Moreover, for every change of frequency, a new design has to be done and a new Qualification Model has to be demonstrated which is a costly measure for space program. Reduction in gain results in degradation of efficiency and thermal performance of the amplifiers which is more important for space applications. Hence, this type of design approach can be considered as non-optimum and needs modification. New technique is proposed in this paper to design an amplifier which can be tuned to the desired frequency band (narrow band) as and when required by switching, covering the wide band and there by resulting in saving of gain per stage and hence efficiency.

4.2.3 Need for the flexible frequency SSPAs for the future Satellite applications:

Flexible frequency SSPAs will find very useful place in new architecture known as of Generic Flexible Payload (GFP). This flexible frequency SSPA is required in flexible payload to meet various requirements like evolving business and political landscapes, the emergence of new technologies and applications, or even a change of orbital location or owner. Moreover, with increasing the number of the satellites, it has now become very difficult to get the sanction of required frequency spectrum from ITU in time and hence sometimes the design has to be changed due to change in frequency. With the help of such SSPAs, the need can be fulfilled without changing the hardware.

The above two problems viz, (i) use of wider bandwidth against the narrowband requirement and (ii) need for redefining the frequency can be achieved by switching the SSPA frequency band by tele-command from ground.

This payload allows the user to redefine the frequency plan, redistribute the transmit power between service regions and change the EIRP according to the specific need without scarifying the satellite performance.

4.3 Theoretical Background:

In order to compare the narrow band design versus wide band design, it is better to understand the factors limiting the wide bandwidth and challenges involved in designing the wide bandwidth amplifier.

Modeling a Common Source (CS) MOSFET amplifier, it will have unity current gain at frequency of unity gain f_T .

$$f_T = \frac{g_m}{2\pi\left(C_{gs} + C_{gd}\right)} \qquad (1)$$

Equation (1) denotes that amplifier frequency also depends on its internal capacitances.

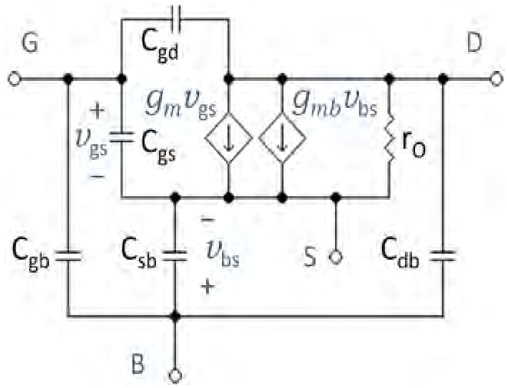


Fig 4.3 High Frequency Model of RF MOSFET

Fig. 4.3 shows the internal parameters which determine the MOSFET behavior. Capacitors mentioned here are as shown in Fig 4.3 Here g_m is the function of voltages and current, it is the trans-conductance gain, so f_T is the function of voltages and currents. For analysis of CS MOSFET few assumptions were made which are as follows.

C_{c1}, C_{c2} and C_s act as perfect short. C_{gs}, C_{gd} act as perfect open. In reality this assumption is true for only limited band of frequencies.

Mid band gain A_m of an amplifier is determined by the following equation.

$$A_m = \left[\frac{-R_g}{R_g + R_{sig}}\right] \cdot (g_m) \cdot ((r_o) \Updownarrow (R_D) \Updownarrow (R_L)) \qquad (2)$$

Gain drops above mid band frequency because C_{gs} and C_{gd} represent imperfect open circuit. Gain drops below mid band frequency because C_s represents imperfect short circuit at lower frequencies.

Gain bandwidth product is given by

$$G.B = (|A_m| \cdot (B.W)) \qquad (3)$$

With constant gain band width product, by increasing band width, mid band gain will be reduced and vice versa. And hence it will not be possible to design a wide band high gain amplifier more than a certain extent. The broad-band microwave amplifier design refers to the problem of power gain roll-off with frequency. The design of broadband amplifier, hence, is more critical than that of narrow-band amplifier design because both S-parameters of the active device and the reflection coefficient looking into the matching networks vary with frequency. In spite of such criticality, designers have to struggle to achieve broadband performance using additional techniques such as Compensating Matching Technique, Negative Feedback Technique, Balanced Structure Technique, Network Synthesis Technique, Distributed or Travelling Wave Technique etc. This calls for a technique to achieve broadband performance by adaptive tuning using switches like Varactor diode for low frequency and PIN diode for high frequency.

4.4 Impedance Matching of an amplifier for switching its operating frequency technique:

According to maximum power transfer theorem, real part and imaginary part are to be conjugate matched. An amplifier using micro-strip line structure will be conjugate matched by adding a line of characteristic impedance, Z_0 ohm, whose length is kept such that it matches real part of impedance of source / load to Z_0 ohm. A micro-strip stub is provided length at this position having length such that it will give negative reactance of source/load reactance. The length of the series stub required to match real part of impedance of source/load of the device, l is given by following equations 4, 5.

$$l = \frac{1}{2\pi} \cdot \left(\tan^{-1}(t)\right).\lambda, t \geq 0 \qquad (4)$$

$$l = \frac{1}{2\pi} \cdot \left(\pi + \tan^{-1}(t)\right).\lambda, t \leq 0 \qquad (5)$$

Where, t is

$$t = \frac{X_L \pm \sqrt{R_L\left[(Z_o - R_L)^2 + (X_L)^2\right] / Z_o}}{(R_L - Z_o)}, R_L \neq (Z_o) \qquad (6)$$

The length of the shunt stub required to match reactive part impedance of source/load of the device, $l_{o.c.stub}$ is given by the equation 7

$$l_{o.c.stub} = \frac{-1}{2\pi} \cdot \left(\tan\left(\frac{B}{Y_o}\right)\right).\lambda \qquad (7)$$

Where, λ is wave length and B is stub Susceptance given by Equation 8

$$B = \frac{R_L^2(t) - (Z_o - X_L(t)) \cdot (X_L + Z_o(t))}{Z_{o\cdot}\left[R_L^2 + (X_L + Z_o \cdot (t))^2\right]} \qquad (8)$$

Thus an amplifier can be matched for source/load by using correct length of stub at specific distance from amplifying device, for a specific frequency. An amplifier is considered linear for conjugate matching. The stub distance from the source and load is a function of frequency so by placing shunt stubs according to frequency; adaptive frequency amplifier can be designed. The stubs are kept disconnected from the series transmission line and connected by switch using a Tele-command. This is the motivation behind this research. This concept of changing the frequency by selecting the stub using PIN diode remotely for geosynchronous satellite has been not presented so far to the best of our knowledge.

4.5 Impedance Matching of an Adaptive Frequency Amplifier:

In order to demonstrate the concept how the amplifier can be designed for frequency switching, three examples using GaAs MESFET, Si RF MOSFET and GaN HFET for high frequency using distributed and low frequency using lumped component matching are explained below. In order to demonstrate the design concepts, load-pull contours for only high power amplifier design has been provided. However, the same has been done for all other examples given below.

The major challenges and complexity involved in providing the flexibility in high power amplifiers are as follows.

(a) So far the power devices manufactured by the manufacturer were internally matched to 50 Ω over the wide bandwidth so it was not possible to change their performance by external matching. To meet the requirement of flexibility, the unmatched devices have to be used. The power devices have very low impedances and poor (VSWR) return loss which requires load pull matching as well as Non-linear (Harmonic Balance) Simulation for varying source and load impendences.

(b) Device selection itself is a great challenge for space segment due to various constraints like de-rating of all parameters, operating temperature range, non-repairable system, overdrive capability, reliability etc.

(c) It is very essential to maintain device's stability, return loss and the gain of the transponder chain with varying impedances and frequencies over the varying temperature ranges from – 10°C to +60°C.

(d) Switching using Varactor and PIN diode needs accurate non-linear modeling and to change their bias remotely is a great challenge for space segment.

(e) The amplifier is designed for space (non-repairable) segment, the thermal management is very important aspect and hence detailed thermal analysis has to be carried out to ensure the highest reliability.

(f) In addition to achieving the required performance, the amplifier must be designed to comply with the Electro Magnetic Interference (EMI) and Electro Magnetic Compatibility (EMC) as per MIL standard 461D and must have sufficient margin (more than 6 dB) to avoid Multipaction.

The following are the design examples for different frequencies for different types of the devices.

1) C-Band Amplifier:

The most commonly used frequency band for satellite communications is C-Band and a large number of SSPAs are used for such applications. An amplifier is designed using a medium power GaAs MESFET at two different center frequencies 4.6 GHz and 4.8 GHz. The stubs are connected to series transmission line using PIN diodes which will be switched ON and OFF depending upon the required frequency operation. The distance and length of the stubs for two different frequencies are given in the Table 4.5.1

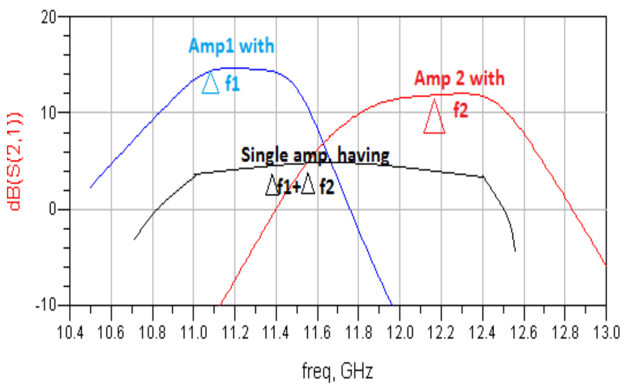
Parameters	4.6 GHz	4.8 GHz
Z_{SM} Ω	$0.023 + j \cdot 0.317$	$0.111 + j \cdot 0.570$
Z_{LM} Ω	$0.02 + j \cdot 0.298$	$0.093 + j \cdot 0.546$
I/P stub distance	$(0.36)\lambda$ mm	$(0.35)\lambda$ mm
I/P stub length	$(0.301)\lambda$ mm	$(0.272)\lambda$ mm
O/P stub distance	$(0.187)\lambda$ mm	$(0.182)\lambda$ mm
O/P stub length	$(0.141)\lambda$ mm	$(0.141)\lambda$ mm

Table 4.5.1 Stub Distances and lengths for different frequencies

By designing the amplifier at 4.6 GHz and at 4.8 GHz with 100 MHz bandwidth, 3 dB gain saving can be achieved as compared to wide band matching of 300 MHz. Using the non-linear models of the devices, the load pull counters have been drawn and optimum impedances are selected for best efficiency and linearity for all designs.

2) Ku-Band Amplifier:

Figure 4.5.1 shows an amplifier designed for narrow band as well as wide band performance and Figure 4.5.2 shows how the stubs are provided in the layout and by selecting the stub position and length the amplifier can be tuned to required frequency bands. The advantage of gain saving in narrow band versus wide band design is also shown in Figure 4.5.1.



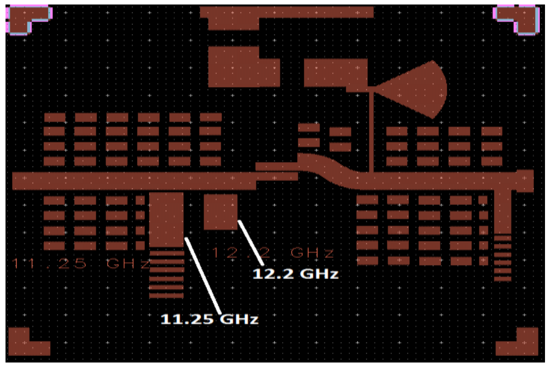


Fig 4.5.1 Gain response at two different frequencies

Fig 4.5.2 Stubs for two different frequencies

All satellites using Ku-Band frequency require a beacon transmitter on-board to track the satellite. This frequency is different for different satellite and very between 10.7 GHz to 12.2 GHz. As and when a new frequency is allotted, a new design has to be done and has to fabricate new SSPA and deliver for the project, which is a time consuming and costly effort. Using this concept, the frequency can be changed even after delivery of the SSPA. Moreover, gain saving of the order of 3 to 4 dB gain can be achieved as compared to wide band matching.

3) UHF-Band High Power Amplifier:

Single stage power amplifier is designed using Si RF MOSFET Power device in UHF band. Using P spice non-linear model of this device, L-C matching network is designed on ADS platform to get the required performance over various bands of interest. Being the space hardware it is also necessary that the variable component (Varactor) used must be space qualified and have sufficient space heritage. So a hyper abrupt Varactor diode from TEMEX having long heritage in space mission has been selected for design. Initially the design is checked with fixed valued capacitors, then these capacitors are replaced with variable trimming capacitors and finally they are replaced with the Varactor diode in parallel with some fixed amount of the capacitors.

As shown in Figure 4.5.3, by changing capacitors and inductors the required performance can be achieved. It is easy to tune capacitor rather than inductor, so here only capacitor tuning is performed. Table I shows that by varying the capacitors C_5, C_6, C_{11} and C_{12} and keeping the inductances L4 = 13nH and L5 = 13.5nH fixed, the amplifier can be tuned for different frequencies. These capacitors need to be replaced by Varactor whose bias needs to be varied remotely by Tele-command.

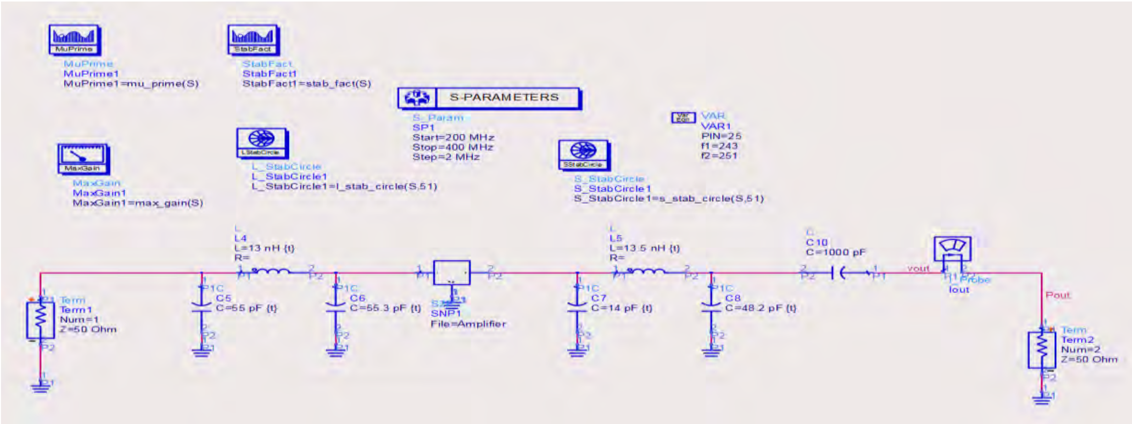


Fig 4.5.3 Schematic of Flexible Frequency Amplifier with Lumped Matching Network

As seen from the table, for different set of capacitors, the gain, gain flatness, bandwidth, output power and stability of the amplifier is maintained within the required specifications. This shows that the amplifier can be tuned from 229 MHz up to 268 MHz with 10 MHz bandwidth for each center frequency. As compared to the topology of adaptive matching network adopted in band reconfigurable high efficiency power amplifier this is simplified topology.

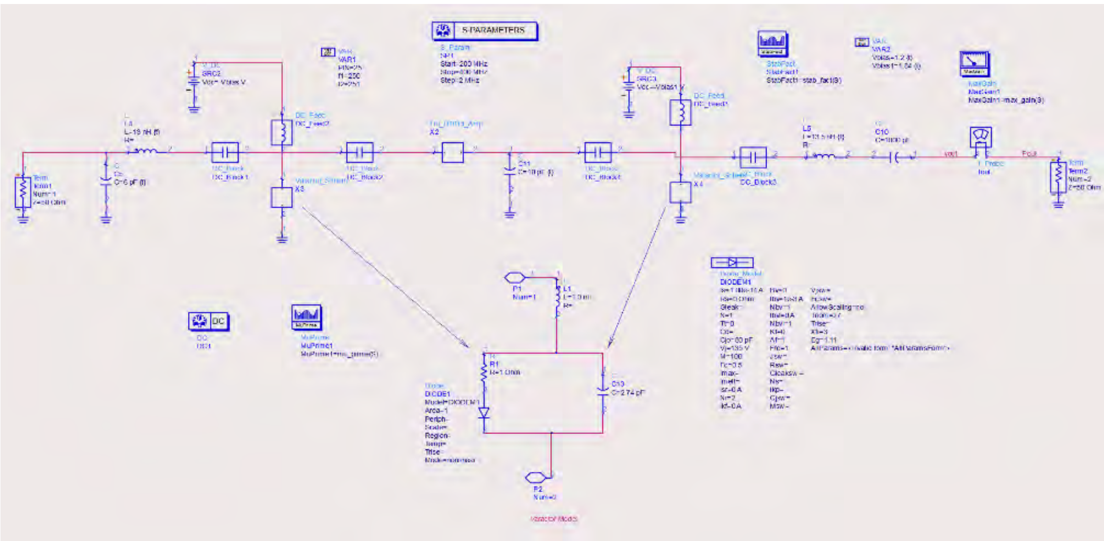


Fig 4.5.4 Schematic Diagram of Flexible Frequency Amplifier with Varactor diode Network

But here the aim is to tune the capacitors remotely so it becomes difficult to realize the hardware if more number of the capacitors is varied due to complexity involved in biasing all these variable capacitors (Varactor). So for simplicity of the hardware realization, only two capacitors are selected for tuning to cover different frequency bands. Table 4.5.3 shows that by changing only two capacitors C_6 and C_{12} and amplifier can be tuned for all those frequencies and keeping inductance L4 = 13nH and L5 = 13.5nH fixed.

These two capacitors are then replaced with Varactor whose bias is varied remotely by tele command from ground. Thus just by varying the bias from the ground, the amplifier can be tuned to operate over the required frequency rather than designing a wide band amplifier. It will be shown in the succeeding section that this switchable narrow band amplifier gives an advantage of gain over the wideband amplifier.

CF Parameters	229 MHz	239 MHz	256 MHz	268 MHz
C_5 (pf)	55.3	49.8	42.3	37.3
C_6 (pf)	56.5	50.5	41	34.5
C_{11} (pf)	24	18	8.8	2.2
C_{12} (pf)	65.8	60	51	46
BW (MHz)	10	10	10	10
Flatness (dB)	0.2	0.2	0.2	0.2
P_1 (dBm)	40.081	39.97	40.1	40.16
Gain (dB)	14	14	14	14

Table 4.5.2 Performance by varying four capacitors

CF Parameters	229 MHz	239 MHz	256 MHz	268 MHz
C_5 (pf)	39.8	39.8	39.8	39.8
C_6 (pf)	56.5	50.5	41	34.5
C_{11} (pf)	13.4	13.4	13.4	13.4
C_{12} (pf)	65.8	60	51	46
BW (MHz)	10	10	10	10
Flatness (dB)	0.2	0.2	0.2	0.2
P_1 (dBm)	40.081	39.972	40.10	40.16
Gain (dB)	14	14	14	14

Table4.5.3 Performance by varying two capacitors

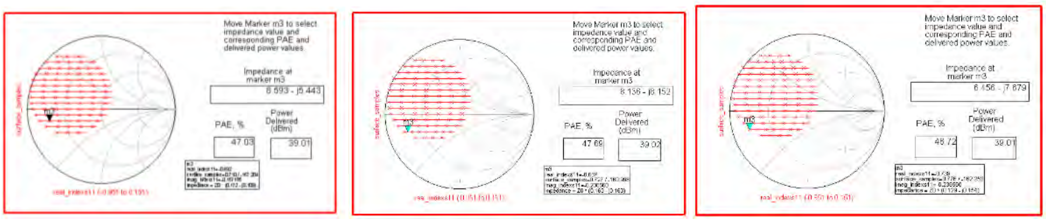
In order to optimize the amplifier for optimum performance, load pull counters are drawn for all selected frequencies and optimum load impedances have been selected for each frequency to achieve the best efficiencies. While changing the capacitance it is also necessary to ensure the stability of the amplifier as well as the return loss for every set value of capacitor.

Finding optimum impedance through Load Pull

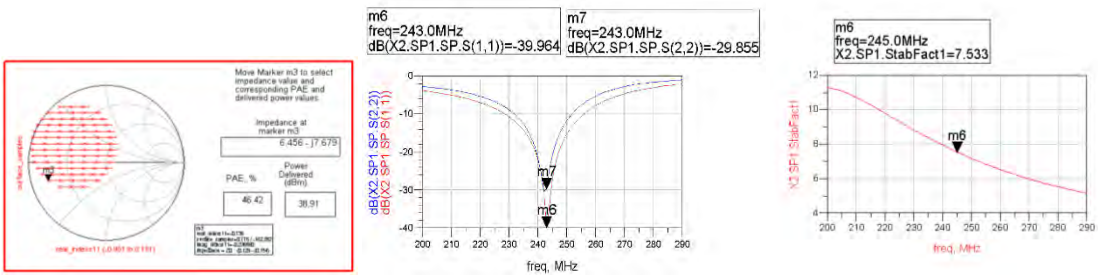
Before the design for switching concept is started, the device is optimized and simulated for optimum performance using load pull techniques. In the load-pull measurement, the performance of the device is tracked through varying source and/or load impedances. Impedance values are varied by the means of either manual or automatic tuners which are controlled by a computer. The computer then fits the measured performance parameters on a gamma source or gamma load plane. Appropriate impedances for source and load are then determined so that the matching networks can be designed. The load pull measurements were carried out in ADS 2008 with the help of the non-linear model provided by the device manufacturer. The load-pull circuit uses harmonic balance simulation in ADS. This iterative simulation calculates the response of large signal circuits driven by either single or multiple sources and tries to find a stationary solution for the non-linear system in the frequency domain.

For UHF Band amplifier design, non-linear model of Si RF MOSFET was available from the manufacturer and Load pull simulations has been done in ADS using HB1Tone_Load Pull design guide with a large-signal/non-linear model of transistor.

Figure 4.5.5 shows the power delivered, Power Added Efficiency (PAE), stability factor and the input and output return loss for different frequencies.



At frequency 229 MHz At frequency 239 MHz At frequency 256 MHz



At frequency 268 MHz

Figure 4.5.5 Output Power and Efficiency response at different frequency

Table 4.5.4 shows the output power, PAE and impedances after load pull matching for all selected frequencies.

Frequency Parameters	229 MHz	239 MHz	256 MHz	268 MHz
Impedance (Ω)	8.593-j5.443	8.136-j8.152	6.456-j7.679	6.456-j7.679
Output power (dBm)	39.01	39.02	39.02	38.91
Efficiency (%)	47.03	47.69	46.72	46.42

Table 4.5.4 O/P power & efficiency at different frequency after load pull

Measured Result:

Pin (dBm)	Pout (dBm)	IRF (@28 V) (Amp)	PDC (Watt)	η (%)
26	40.1	0.8	22.4	45.66
25	39.4	0.74	20.72	42.70
24	38.9	0.66	18.481	41.60
23	38.15	0.60	16.8	38.00

Table 4.5.5 Measured result of a single stage 40 Watt amplifier

The measured result of 40 Watt amplifier using RF MOSFET used as a driver for the final 100 watt RF MOSFET at UHF band is shown in Table 4.5.5. The efficiency of this amplifier is low as compared to that at rated output power as the amplifier is in near saturation in order to achieve the linearity requirement for multi tone operation. This amplifier has been used to demonstrate the frequency switching technique using Tele command data as described in the section 5.7.

4) GaN High Power Amplifier:

The most important advantage of this approach is found in high power SSPAs using GaN devices. It is possible to cover whole band from 1 to 2.7 GHz using unmatched GaN device delivering output power of 180 watts with a gain of 10 dB using negative feedback. The same device when designed for narrow band (30 MHz) matching each for L1, L5 and S band, same power can be achieved with a gain of 13 dB resulting in saving of 3 dB gain. This improves the thermal performance of the device as well as need for lower power device as compared to wide band case. Presently the navigation satellites use three different TWTAs for L1, L5 and S Band as the single TWTA cannot cover all three bands. A wideband amplifier has been designed using GaN HEMT which covers all three bands with almost equal efficiency as TWTA but for individual band there gain saving of 3 dB. The TWTA will never compete this type of SSPA and hence remarkable saving of weight, size, DC power and cost. High power GaN HEMT device having capability of 200 Watt has been selected our design. This device has two independent 120 watt devices which have to be combined using some type of combiner to get 200 Watt output power. The large signal model of 120 Watt device was available from the manufacturer. This device is used for the load pull analysis as this device has the same characteristics as that of 200 Watt device, the only difference is that two 120 watt need to be combined.

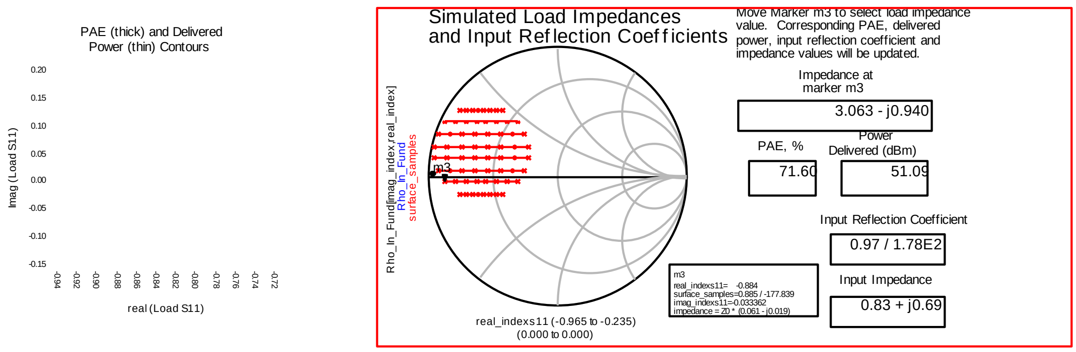


Fig 4.5.6 Load pull counters for GaN HEMT power device

Figure 4.5.6 shows the load pull counters of power delivered, Power Added Efficiency (PAE), stability factor and the input and output return loss for 1.3 GHz using GaN HEMT power device. Similar counters have been drawn for other frequencies for L band also.

Frequency Parameters	1.1 GHz	1.3 GHz	1.5 GHz
Impedance (Ω)	5.16-j2.075	3.063-j0.940	2.810-j1.729
Output power (dBm)	51.01	51.09	52.07
Efficiency (%)	70.40	71.60	72.08

Table 4.5.6 O/P power & efficiency at different frequency after load pull

Table 4.5.6 gives output power and efficiency for different frequencies after load pull technique. The amplifier can be tuned for different frequencies for different load impedance with likely equal output power and efficiency. With this type of design, the whole L and S band can be covered by switching between the different frequencies resulting in replacement of TWTA and hence mass and cost.

Measured Result

P_{in} (dBm)	P_{out} (dBm)	IRF (@28 V (Amp)	PDC (Watt)	η (%)
39	53.0	11.7	327.6	58.5
38	52.6	11.1	310.8	56.3
37	52.0	10.3	288.4	52.7
36	51.2	9.4	263.2	48.2

Table 4.5.7 Measured result of a single stage 200 Watt amplifier module

The measured result of 200 Watt amplifier using GaN HEMT at L Band is shown in Table 4.5.7. The efficiency of this amplifier is low as compared to the simulated results as the amplifier is not operated its full saturation of 4 dB gain compression point.

4.6 Advantage of narrow band versus wide band design in terms of thermal management for space applications:

As seen from the Table 4.6.1, a remarkable gain saving can be achieved when amplifier is designed for narrow band as compared to wide band. By varying only two capacitors C6 and C8, the amplifier can be tuned for required bandwidth is shown in Figure 4.6.1. While designing this type of amplifier, another advantage is gained due to switching which is explained below. To understand the advantage of the narrow band design versus wide band design, the following line up of an UHF band power amplifier is considered.

In order to achieve 100 watt CW RF output power over the frequency band 242 MHz to 254 MHz, two RF MOSFETs are employed in balanced configuration. Each RF MOSFET is used in push-pull configuration. The RF gain of this balanced configuration is 10 dB. This stage is driven by another RF MOSFET which delivers the required RF output power of 10 watts. This device has RF gain of 10.66 dB over the wide bandwidth of 50 MHz and 14.27 dB over 12 MHz which is 3.61 dB more. If the similar concept is applied to the final stage also, total gain saving of 7.22 dB will be is achieved. In addition to the gain saving, another advantage of DC power saving can be explained as below.

If the gain of the final device is 10 dB, it needs a device of 10 watt output to drive it but if the gain is 13 dB, it needs only 5-watt device. Similarly, the driver device needs 250 mW device instead of 1-watt device. It is well known that devices with higher output power are costlier to the lower power devices. This results in saving of more than 5 watts DC power and improvement of the channel temperature of 5^{O}C due to less dissipation of 5 watts in final device as explained below. Thermal resistance R_{th} of this device is 1^{O} C/W so saving of P_{diss} of 5 watt results in reduction of channel temperature of 5^{O} C and hence improves reliability.

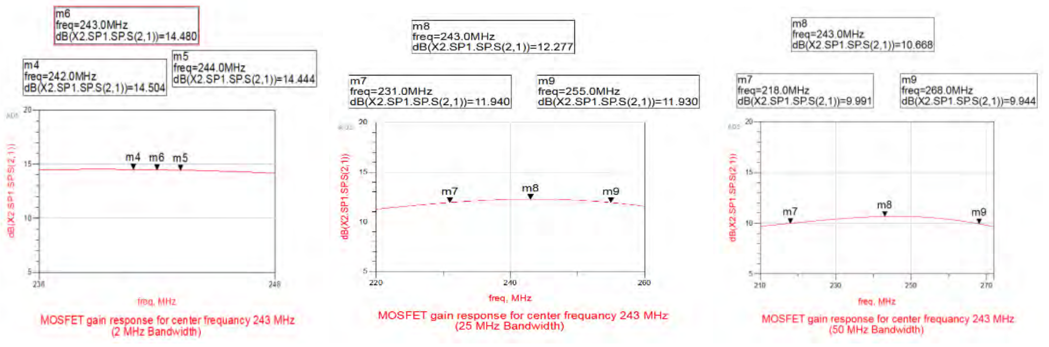


Figure 4.6.1 Simulated results for Gain versus different bandwidth

Parameters Frequency Band	C5 (pF)	C6 (pF)	C7 (pF)	C8 (pF)	Gain (dB) at CF	Flatness (dB)
2 MHz (242-244)	55	56.6	14	51.2	14.48	0.06
12 MHz (237-249)	55	55.3	14	48.4	14.27	0.25
25 MHz (231-255)	55	52.5	14	34	12.27	0.34
50 MHz (218-268)	55	38.7	14	26.1	10.66	0.66

Table 4.6.1 Device performance at different frequency band with matching capacitor values

As described in above section, load pull counters are drawn for various bandwidths (2 MHz to 50 MHz) and corresponding efficiency improvement can be seen from the above Table 4.6.2. To cover the redundancy (4:3), SSPA was designed for 12 MHz bandwidth whereas the actual usable bandwidth was 2 MHz for 100-watt UHF SSPA which is already operational in Geostationary orbit for last 3 years.

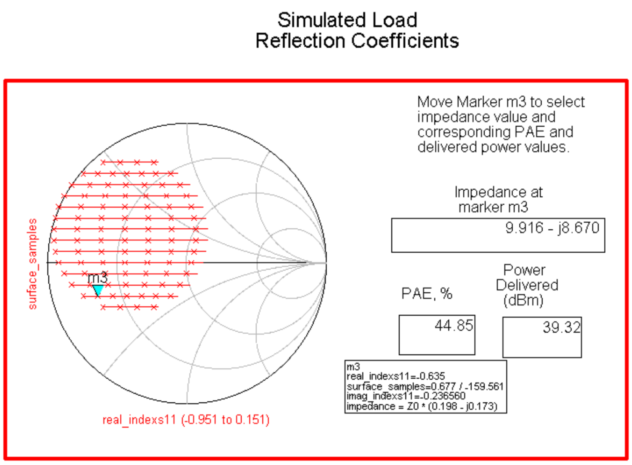


Figure 4.6.2 Output Power and efficiency response at frequency 243 MHz

Bandwidth (CF=243 MHz)	Efficiency (%)	Output Power (dBm)
2 MHz	44.85	39.32
12 MHz	41.50	39.14
25 MHz	38.67	38.88
50 MHz	36.95	38.67

Table 4.6.2 O/P power & efficiency at center frequency 243 MHz with different bandwidth after load pull

With this concept about 5 % efficiency improvement can be achieved resulting in DC power saving of approximately 40 watts per SSPA. For this satellite the channels were limited to 3 numbers but for future satellite when more numbers of channels are defined the improvement in efficiency can be still higher (10 %).

4.7 Control circuit to operate the switch by Tele-command

As explained in above discussion, in order to change the frequency band, it is necessary to change the bias voltage of the Varactor remotely. This is accomplished by the following mechanism known as Tele-command attenuator circuit. The circuit consists of an Input Buffer, Schmitt Trigger, Serial to Parallel Converter and a Latch in cascade configuration as shown in the Fig 4.7.1.

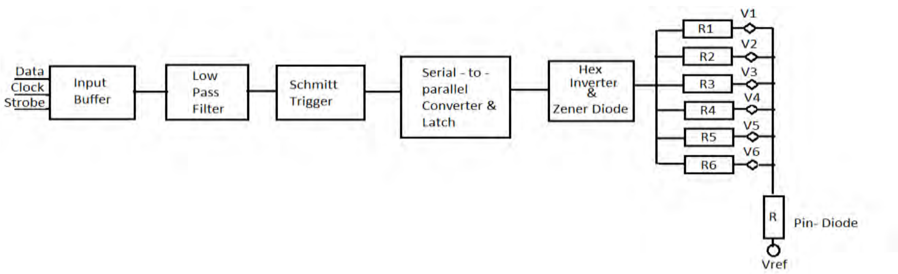


Fig. 4.7.1. Tele-commendable Attenuator circuit to change the voltage to PIN or Varactor Diode

Spacecraft receives serial data which is converted into parallel data and this parallel data is converted into required Analog signal. The resistance of each resistor can be adjusted to generate required voltage for Varactor diode by Data stream from the ground. A two stage amplifier using RF MOSFET has been designed and tested using Tele-command generator and required performance has been achieved. As seen for the Table 4.7.1 by applying the data command, the voltage of the Varactor will be changed and accordingly the frequency of the amplifier can be tuned to the required band.

Data command	Varactor Voltage (Volt)	Gain (dB)	Centre frequency (MHz)	Data command	Varactor Voltage (Volt)	Gain (dB)	Centre frequency (MHz)
0000	0	30	240	1000	0.8	28.45	245.57
0001	0.1	30	240.82	1001	0.9	28.29	245.92
0010	0.2	29.85	241.72	1010	1	28.18	246.59
0011	0.3	29.54	242.25	1011	1.1	28.07	246.97
0100	0.4	29.31	243.15	1100	1.2	27.98	247.35
0101	0.5	29.09	243.87	1101	1.3	27.73	247.72
0110	0.6	28.88	244.78	1110	1.4	27.65	248.32
0111	0.7	28.65	245.02	1111	1.5	27.56	248.55

Table 4.7.1: Measured result of two stage amplifier for different freq. by varying Varactor voltage

Similar work has been presented in by D. Rosolowski, W. Wojtasiak and T. Morawski in their work, “A S-band 7 W GaN HEMT adaptive power amplifier"[8]. The work does not give much detail of design concepts and the technique by which the frequency is changed remotely. Moreover, the work is for ground use and for small signal design (7 watt) where not much challenges are involved as compere to the high power amplifier. The work presented in here is for geo-stationary satellite application and for higher power (40 watts and 200 watt) design.

Conclusion:

By using the concept of flexible frequency amplifier, the operating frequency and the bandwidth can be changed easily by issuing command from the ground for satellite communications. For lower frequency bands, the single SSPA can be used for three different frequency bands (L1, L5 and S band) by switching, which leads to many advantages like higher gain, higher output power, higher efficiency, and lowered channel temperature, compared to a single fixed frequency wide band amplifier. This concept will also help the users to use the existing hardware even if the frequency changes which is not the case for existing fixed frequency hardware. Using GaN devices and such technique, it has now become possible to replace the TWTAs up to C band with a comparable electrical performance and saving in weight, volume and cost. Future satellite communication payload will be demanding flexibility so this concept will be very useful for Generic Flexible Payload. Besides flexibility, the most important parameters for space segment like DC power saving and improved reliability are achieved.

REFERENCES:

[1] Agile Equipment for an Advanced Ku/Ka Satellite. ESA Workshop on Advanced Flexible Telecom Payloads 18-20 November 2008 at ESTEC,

[2] An Overview of the Generic Flexible Payload Program and Future Technologies for Optimizing Payloads to Business Needs 2nd ESA Workshop on Advanced Flexible Telecom Payloads (17-19 April 2012, ESA-ESTEC, Noordwijk – The Netherlands).

[3] Frequency Agile 14/12GHz Down converter for Flexible Communications Payloads 2nd ESA Workshop on Advanced Flexible Telecom Payloads (17-19 April 2012, ESA-ESTEC, Noordwijk – The Netherlands).

[4] L. Kuzu, A. F. Yagli, M. Gokten and V. Yanikgonul, "Reliability analysis of TUSAT satellite communication payload," *Satellite Telecommunications* (ESTEL), 2012 IEEE First AESS European Conference on, Rome, 2012, pp. 1-5

[5] Department of Defense, Electronic Reliability Design Handbook, "MIL-HDBK-338, Volume 1 of 2", October 1984.

[6] K.C. Kapur, L.R. Lamburson, Reliability in Engineering Design, New York: John Wiley & Sons, 1977

[7] Flexible payloads for telecommunication satellites - a Thales perspective Nathalie Font, Cyrille Blosse, Patrick Lautier, Arnaud Barthère, and Philippe Voisin 32nd AIAA International Communications Satellite Systems Conference. SPACE Conferences and Exposition, (AIAA 2014-4382).

[8] D. Rosolowski, W. Wojtasiak and T. Morawski, "A S-band 7 W GaN HEMT adaptive power amplifier," *2012* 19th International Conference on Microwaves, Radar & Wireless Communications, Warsaw, 2012, pp. 304-307.doi: 10.1109/MIKON.2012. "

CHAPTER 5
Adaptive Thermal Management Technique to Improve the Efficiency of the SSPA for Geo-Synchronous Satellites

5.0 Objective:

For any sub-system, the prime requirement of the purchaser (user) is the useful life of the unit which is purchased. For heat dissipating units like amplifiers, their life is determined by the techniques by which their heat can be controlled and the device can be kept cooled. As compared to ground hardware, the space hardware needs proper heat removal due to only conduction is the medium by which the heat can be transferred so sufficient margins are kept in the design to ensure the reliable life over the specified period. The designs made so far are with fixed parameters which are non-optimal so some technique like flexibility can improve the performance of the amplifier. A new thermal management technique is required to improve the efficiency of Solid State Power Amplifier (SSPA) for space applications. The SSPA has been struggling to compete long heritage Travelling Wave Tube Amplifier (TWTA) but due to its' lower efficiency as compared to TWTA, it could not replace TWTA for high power applications. With advancement of Gallium Nitride (GaN) power device it has now became possible to reach up to the power level of TWTA. Even with GaN SSPA, the efficiency is still lower than TWTA so it is necessary to improve the efficiency of SSPA. In addition to flexible output power and flexible frequency SSPA, one more adaptive thermal management technique is presented here which improves the efficiency of the SSPA thereby resulting in saving of costly DC power generation on-board and reducing the DC power dissipation. Another technique to improve the gain and output power variation over the specified temperature limits is also presented to improve the efficiency as well as cost.

5.1 Introduction:

Microwave Power Amplifiers (MPA) are the most important sub-systems for onboard communications satellites as they consume the highest (80 to 90 %) spacecraft bus power, major contributor to mass budget of payload, determining the non-linearity performance of the payload, the major role player for the spacecraft thermal management and finally the reliability decider of the satellite. The reliability of the spacecraft is mainly determined by thermal management and the thermal management is dependent on the thermal dissipation so the DC to RF efficiency (power added efficiency) is the prime factor determining the type of MPA. TWTAs and SSPAs are two competitors for selection as Microwave Power Amplifier (MPA) for space communications payload. Efficiency being the prime requirement, TWTA has been leading the SSPA in competition due to its' higher efficiency even though SSPAs are advantageous in terms of mass, weight, linearity and cost. The main limiting factor for lower efficiency of SSPA is the device's channel temperature which is limited by established de-rating guidelines. It is necessary for SSPA designers to find out some techniques by which the SSPA can defeat the TWTAs. A new idea for improvement of efficiency of SSPA is presented, which recommends use of single device in place of a conventional approach of balanced configuration for initial life and then switch over to balance configuration for remaining period of life if the channel temperature exceeds the specified de-rating guidelines.

5.2 SSPA versus TWTA:

TWTA is high frequency, high efficiency, high power amplifier by structure whereas SSPA is solid state device base technology which delivers high RF output power by parallel combination of devices. The device output power is limited by manufacturing process as well as type of the material GaAs or GaN used for its' fabrication. When many devices are combined, the overall efficiency gets degraded. With development of new device technology of GaN, it has now become possible to achieve higher RF output power comparable with TWTA at lower frequencies. As explained in [3], the efficiency can be improved by using dynamic biasing or flexible output SSPA as well as flexible frequency SSPA [4]. Besides these approaches, it is necessary to work towards new research which allows improvement of efficiency. One such new idea is presented here. Solid state device performance is highly dependent on temperature which puts a limit on its' efficiency as the de-rating guidelines [1-2] does not allow the SSPA designer to operate the power device beyond certain channel temperature. Because of such reason, the power FET cannot be operated at the device manufacturer's claimed efficiency which may be 70 to 90 %. So far the device channel temperature is calculated at the worst case temperature limits, which is the predicted extreme temperature of the satellite base plate rather than the real time value. We propose to use the real time temperature value to calculate the channel temperature which results in improvement of efficiency of the SSPA for the half of the life of the satellite.

5.3 Margins Provided in Thermal design of Geo Synchronous Satellite:

As compared to the ground segment of the Satellite Communications system, the space segment is non repairable so extreme care is taken to ensure that the hardware used is with highest reliability and with zero defect. For space hardware, the reliability calculations are carried out using Mean Time to Failure (MTTF) rather than Mean Time Between Failure (MTBF). Moreover, the hardware made for a particular type of satellite remains unaltered for 12 to 15 years of satellite life. So sufficient margins are kept while designing the space hardware to account for variation of important parameters due to temperature variations as well as aging to ensure the specified performance at the end of the satellite life. Few examples are as follows;

(a) The performance of the active subsystems like TWTAs, SSPAs, Receiver etc. changes mainly due to change in temperature inside the spacecraft as well as aging of the components and ionic space radiations. So the Beginning Of Life (BOL) performance of SSPA/TWTA degrades by considerable amount of 0.5 to 1 dB output power at the End Of Life (EOL) so this much amount of additional margin is kept while designing satellite.

(b) The spacecraft in Geostationary orbit is exposed to extreme temperatures as it is in the outer radiation belt and hence the temperatures in the cold space case is 2.76 K and in hot Sun case is 5600 K [5]. The satellite payload components cannot withstand this much amount of temperatures so it is necessary to maintain the temperature within the acceptable limit (-10˚C to + 55˚C) so that the payload components can be operated safely for specified life span (12 to 18 years) of satellite. In order to maintain the temperature within this acceptable limit, passive and active thermal management is carried out. The satellite is wrapped in Multi-Layer Insulator (MLI) and Optical Surface Reflector (OSR) windows are provided to radiate the waste heat. Thermal paint, thermal grease, thermal filler materials and Heat pipes etc. are used for passive thermal management [6].

5.4. Degradation of Spacecraft Thermal Materials:

The materials used on exterior spacecraft surfaces are subjected to many environmental threats like photon radiation, charged particle radiation, temperature effects and thermal cycling, impact from micrometeoroids and debris, contamination, and low earth orbit atomic oxygen. The important properties of external spacecraft surface like structural integrity and thermo-optical properties degrades when these materials become too thin or brittle to support a required load or when protective thermal insulation film layer crack and peel away from the spacecraft. Degradation of these thermo-optical properties of material can cause an undesirable change in temperature of the spacecraft or its components.

It is very difficult to predict accurately the degree to which the space environment degrades or damages materials. Ground laboratory testing in a timely manner using accelerated levels helps to predict the temperature range in which the satellite temperature can be controlled. As explained in [7-8], the temperature increase of satellite at the end of long term mission is mainly caused by degradation of solar absorptive {αs) of the surface thermal control coatings under space environment. Various tests are carried out to determine the degradation and the worst case value is taken into consideration for thermal control. For example, the BOL value of alpha (αs) for OSR is 0.11 but the EOL value is taken to be 0.27 which is higher than the acceptable value [8].

5.5 Satellite Reliability dependence on Temperature:

Among all sub-systems, the thermal management is absolutely critical for high power SSPAs as they are the most heat dissipative elements in the satellite so more attention is required for SSPA thermal design. The most challenging task for a power amplifier designer is to achieve the optimum output power with good efficiency, linearity and sufficient margin for the device's Channel (Junction) temperature. The device manufacturers specify very high efficiency in their catalogue which is true for ground applications but for long life space mission, it is very difficult to meet required performance as the designers have to follow the ESA/MIL de-rating guidelines [1-2]. The designers have to struggle a lot to make trade-offs between output power, efficiency and linearity to achieve the maximum allowable channel temperature which is 110˚C for GaAs MESFETs for 15 years of life.

The Arrhenius equation is the basis for calculating device reliability [9-10].

$$\ln\left(\frac{t2}{t1}\right) = \frac{Ea}{k}\cdot\left(\frac{1}{T2} - \frac{1}{T1}\right) \quad (1)$$

Where:

$t1$= reference time to failure at reference temperature T1

$t2$= time to failure at temperature T2

Ea =Activation energy (unique to process)

T1=Reference temperature (Kelvin) for failure time t1,

T2=Temperature (Kelvin) to calculate failure time t2

Equation (1) calculates median time (t2) of failure based upon a known median time (t1) of failure, failure activation energy (Ea) and failure temperature (T1). Activation energy is the amount of energy required to induce a specified failure mechanism in a semiconductor technology.

The reliability is highly dependent on the devices' operating temperature. So research on improving the margins for channel temperature of the device is necessary. In order to provide such margins, the satellite is over designed and hence needs the sub-systems with more than the optimal performance such as RF output power, DC power etc. which increases the cost of the satellite.

5.6 Present Satellite Thermal Management technique:

It has now become possible to design the satellite for optimal performance and later as and when required should be made flexible in terms of performance. [3-4] So far flexibility in terms of output power and frequency has been presented but flexibility in terms of thermal management has not been presented.

Here the flexibility in terms of the most critical aspect of satellite design i.e. thermal management is presented. The Solid State Power Amplifiers (SSPAs) are considered as the most challenging subsystem for the satellite design due to their large number, mass, DC power consumption, linearity performance, thermal constraints and reliability.

It is necessary to get two controversial parameters together for SSPAs i.e. linearity and efficiency. To get higher efficiency, SSPA must be operated in class B but it degrades linearity and if operated in class A, it gives better linearity but efficiency degrades. So to get optimal performances SSPAs, final devices are operated in class AB. The device efficiency achieved in class AB is about 50% to 60 % so half the DC power gets converted in to heat which raises satellite panel temperature. Efficient heat removal from the device is very important for safe & reliable operation. Because its' channel temperature increase results in life reduction of the device. For each component there is an established temperature up to which it can be utilized satisfactorily and beyond this limit the devices' life degrades. Each 10˚C temperature increment reduces the component life by 50%. Conversely, each 10˚C temperature reduction increases component life by 100%. [11] In order to provide safe operation all active sub-system is designed to operate between -10˚ C to 60˚ C for 15 years of life.

So far the reliability calculations are carried out for worst case conditions only so sufficient margins are provided in order not to come across any abnormal behavior. Based on the studies carried out for degradation of various thermal coating materials and the temperature data available from various satellites already launched and completed the life, it is found that the satellite becomes hotter at the end of the life. Initially, after the launch of the satellite, for few years, the thermal management system provides 100% efficiency and hence the base plate temperature is maintained at about ambient temperature (25˚C). Later, the thermal performance degrades due to degradation and aging of thermal control system components so the base plate temperature may rise by about 2 to 3 ˚C per year so the extreme temperature may reach up to 60˚C at the end of life (15 years). Because of this reason, the channel temperature is calculated with base plate temperature at extreme temperature which is the worst case value of +60˚C.

5.7 Single device versus balanced configuration of Power Amplifier:

In order to better understand the proposed concept, two different design examples are presented here. The first example explains design and development of 100 Watt SSPA at UHF band using RF MOSFET and the second using Gallium Nitride (GaN) HFET. The UHF amplifier has been designed and delivered to Geo satellite and is in operation in space for last three years. [12] The following example gives designed and measured data of the final stage of an amplifier and also explains the need for two devices rather than single device to meet the channel temperature for space use.

An RF MOSFET with the following specification has been used in the design.

RF output power (nominal)Pout	: 100 Watts
Bandwidth	: 240-260 MHz
Power added efficiency (η)	: 60 %
Thermal Resistance of device	: 0.7˚C/W

Figure 5.7.1 shows the power levels of Single stage amplifier used as final power device of 100 Watt UHF SSPA which is capable of delivering the required power but in order to meet the de-rating guidelines, this configuration is not recommended for space use. According to the de-rating guidelines [10], the channel temperature must be below 110˚C for safe mission. The thermal management system ensures the channel temperature to be less than 110˚C for 15 years of life. To achieve this number, the base plate temperature must be maintained at 40˚C at the end of the life of 15 years which may not possible due to degradation of various material used for thermal management as explained above. The only alternative is to reduce the power dissipation as thermal resistances are fixed number which cannot be improved much. The only

option left with designer to reduce the power dissipation is to use two devices in balance configuration as shown in figure 5.7.2.

The channel temperature of FET is calculated using the following equation.

$$Tch = Rth * Pdissipation + Ta \qquad (2)$$

Where:

Tch = Device (FET) Channel temperature

Ta = Base plate temperature (ambient temperature)

$Pdissipation$= Total power dissipation as heat

Rth = Effective thermal resistance

The channel temperature calculated using above theoretical calculation is verified using the Finite Element Modeling (FEM) simulation also.

If there is no constrain regarding the channel temperature, only single can be used to derive the required power as shown in the figure 5.7.1.

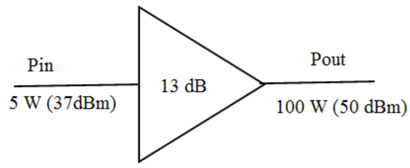


Figure 5.7.1: Single Stage Amplifier of High Power SSPA at UHF band

The balanced configuration consists of a divider, two devices in parallel and a combiner as shown in Figure 5.7.2. This is the most commonly used configuration in the high power SSPAs to meet the de-rating guidelines. Both these configurations are compared and results are summarized in Table: I.

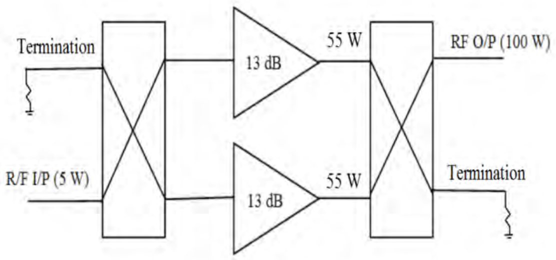


Figure 5.7.2: Balanced Configuration using two devices in parallel

According to the de-rating guidelines [3], the channel temperature must be below 110˚C for safe mission. The thermal management system ensures the channel temperature to be less than 110˚C for 15 years of life. To achieve this number, the base plate temperature must be maintained at 40˚C at the end of the life of 15 years which is not possible due to degradation of various material used for thermal management as explained above. The only alternative is to reduce the Pdissipation as thermal resistances are fixed number which cannot be improved much. The only option left with designer is to use two such devices are used in balance configuration in order to reduce Pdissipation as follow. The balanced configuration consists of a divider, two devices in parallel and a combiner as shown in Figure 5.7.1.

Device Configuration	Pout (watt)	P_{DC} (watt)	$P_{dissipation}$ (watt)	Device η (%)	Effective Rth (˚C/Watt)	Tch (˚C) @ 60 ˚C base plate	Tch (˚C) @ 40 ˚C base plate	SSPA η (%)
Single Device	100	170	70	60	1.0	130	110	45
After 8 years when the base plate reaches above 40 ˚C								
Each device of Push-pull Configuration	55	105 (Total 210)	50	55	1.0	110		37

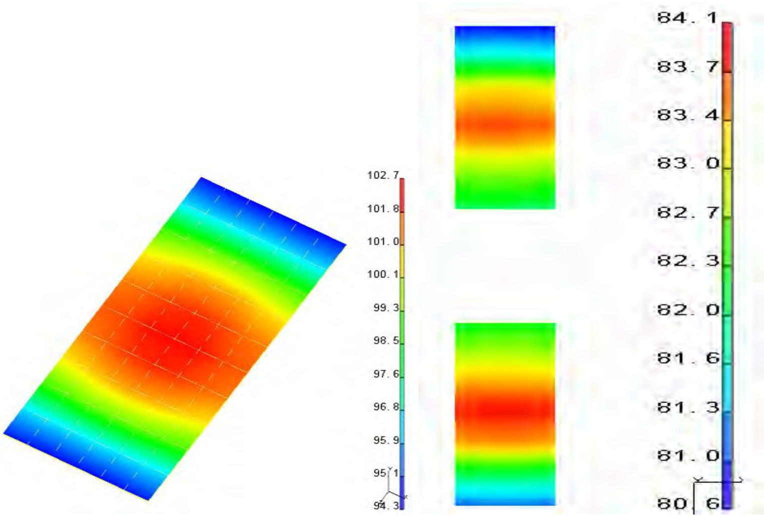
Table: 5.7.1 Measured results of single stage versus balanced configuration of 100 Watt SSPA

As seen from the Table 5.7.1, during initial period of the satellite life, until the base plate temperature reaches 40˚C, single device configuration will ensure the channel temperature below 110˚C and later (approximately after 8 years) when the base plate crosses 40˚C, the balance configuration is required. An improvement of 7% efficiency is considerable for space segment.

Thus, 40 Watt (210-170) more DC power per SSPA is required for balanced configuration option than the single device option. Moreover, the power dissipation is also 30 Watt (100-70) more in case of balanced configuration than single device option. Generally, 12 SSPAs are used a satellite so these number will be 12 times the number for one SSPA.

This results in more demand of DC power from satellite BUS and more thermal dissipation to manage for thermal management. Even though the single device option is better than balanced configuration, so far balanced configuration has been used in space to meet the de-rating guidelines. This calls for new technology which is presented here.

In order to estimate the case temperature, Finite Element Modeling (FEM) analysis is carried out for both the options and accordingly the channel temperature is calculated. Figure 5.7.3 shows the counters of the case temperature for both the cases.



Case temperature is 102 °C
for Single Stage Amplifier configuration

Case temperature is 84 °C
for Balanced Configuration Amplifier

Figure:5.7.3 Thermal Counters of the case temperature for single stage and Balanced configuration

5.8 Proposed scheme using switch

We propose a scheme which allows reducing the dissipation in accordance with the base plate temperature. It is proposed to carry out the thermal analysis at real time temperature i.e. at the actual base plate temperature rather than at extreme hot temperature (+60˚C) while maintaining the de-rating guidelines. This can be achieved by operating only one device until its channel temperature reaches the specified limit of 110˚C and then switch over to balance configuration if the device's channel temperature crosses the limit.

In this condition, the modified balanced configuration as shown in figure 4 will be used which consists of additional coaxial switches in addition to the standard balanced configuration. In standard balanced configuration, a divider divides the incoming RF signal in to two arms which is amplified by two amplifiers in parallel and then combined to deliver the RF output. The switches are used to switchover from single device option to balanced configuration option. To achieve this, initially the combiner needs to be bypassed for single device option and later the combiner is brought back for balanced configuration.

The proposed Balanced Configuration for RF MOSFET is shown in figure 5.8.

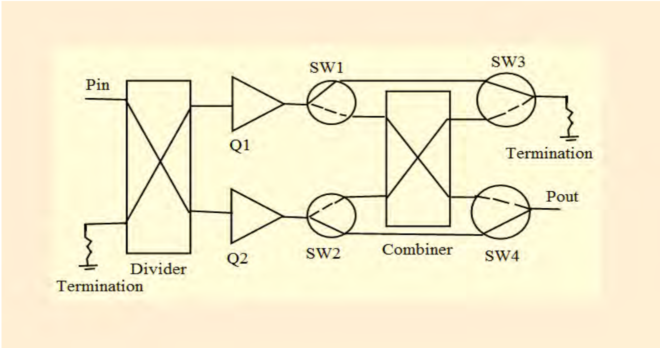


Figure 5.8: Proposed Balanced Configuration for RF MOSFET

The circuit description is as follows.

The High Power Amplifier (HPA) is driven by medium power amplifier which delivers 10 Watt RF power to HPA. It is divided into two equal amplitudes (approximately 5 Watt), 90 degrees out of phase, signals which drives two high power amplifier stages in balanced configuration. Initially only one device (upper) Q1 will be in operation so another device (lower) Q2 will be off, but will be receiving the RF even when its' DC biasing will be off. This requires the device capable of operating in such conditions. Later, when both the devices need to be operated, the DC biasing of both the devices need to be changed.

Challenges involved in order to provide such flexibility are as follows.

(1) So far the switches have been operated at the sub-system level only not at the device level so while changing the switch position the device must represent load mismatch equal to 30:1means the amplifier must be stable for full reflections.

(2) When only one device is in operation another device will be in switched off condition which requires a device capable of withstanding the higher power level of RF input in absence of DC bias.

(3) While switching over from single device option to balanced configuration, the RF input to the devices and bias of the device has to be adjusted which needs special technique.

(4) Temperature telemetries have to be provided in order to prevent any sudden early rise in base plate temperature.

The challenges 1 and 2 have been successfully resolved by selection of a space qualified RF MOSFET with load mismatch of 30:1 and by designing in push-pull configuration. It was tested for all load conditions including all phases. [12] But when any device other than RF MOSFET is to be used then special kind of mechanism has to be used as explained in next section.

The challenge 3 calls for a technique called dynamic biasing approach which has been successfully demonstrated by the authors in [3], [13].

To meet the requirement 4, the various thermistors (10 KΩ) have been placed at various places like device case, package floor, package base and device's top lid which give the temperature details as telemetries and accordingly the device can be switched off to protect it from exceeding temperature.

This scheme has various disadvantages like, inclusion of two switches, their insertion loss of 0.15 dB per switch and complexity involved in dynamic biasing of the device design. But the advantages gained are much higher than these disadvantages. Additional loss of0.3 dB is compensated if the combiner is used then it's loss as well as loss due to amplitude and phase imbalance so no significant disadvantage is noticed. The dynamic biasing can be achieved for RF MOSFET as the devices with 30:1 are available so there is no reliability concerned.

As shown in the figure, initially only one device is in operation so switch SW1 and SW3 will be ON whereas the switches SW2 and SW4 will be OFF.

As soon as the base plate temperature reaches 40˚C, the switches' positions will be changed from ground command such that switches SW2 and SW4 will be ON so that the balance configuration delivers the required power.

5.9 Single Gallium Nitride (GaN) based SSPA

The similar concept has been applied for wide band gap GaN (Gallium Nitride) based SSPA which is the dominant candidate to replace the TWTAs. Based on the life test data, the maximum allowable channel temperature for GaN device is 160˚C due to the wideband gap material technology. The concept described can be applied to GaN based SSPA as follows.

For L-band GaN SSPA, the required output can be achieved with only single device but channel temperature becomes higher than the specified limit so two devices are used in balanced configuration

GaN HEMT with the following specification has been used in the design.

RF output power (nominal) Pout	: 150 Watts
Bandwidth	: 1110-1130 MHz
Power added efficiency (η)	: 55 %
Thermal Resistance of device	: 0.7˚C/W

Device Configuration	Pout (watt)	P_{DC} (watt)	$P_{dissipation}$ (watt)	Device η (%)	Effective Rth (˚C/Watt)	Tch (˚C) @ 60 ˚C base plate	Tch (˚C) @ 40 ˚C base plate	SSPA η (%)
Single Device	150	272	122	55	1.0	182	162	45
After 8 years when the base plate reaches above 40 ˚C								
Each device of Push-pull Configuration	90	180 (Total 360)	90	50	1.0	150		38

Table 5.9.2 Measured results of single stage versus balanced configuration of 150 Watt GaN SSPA

As seen from the Table 5.9.2, during initial period of the satellite life, until the base plate temperature reaches 40˚C, single device configuration will ensure the channel temperature below 160˚C and later (approximately after 8 years) when the base plate crosses 40˚C, the balance configuration is required. An improvement of 7% efficiency is considerable for space segment.

Thus, in case of GaN SSPAs 88 Watt (360-272) more DC power is required for balanced configuration option than single device option. Moreover, the power dissipation is also 58 Watt (180-122) more in case of balanced configuration than single device option.

The concept explained in the case of RF MOSFET cannot be applied directly for this type of the devices due to following reasons.

The GaN device do not have the load mismatch of 30:1 similar to RF MOSFET so it is necessary to cut off the RF input signal to the device (lower) which is not in operation. A switch is introduced in the lower device Q2 path, which will cut off the RF signal reaching the device so the device will not be get damaged when DC is off and RF is applied to it. Proposed Balanced Configuration for GaN is shown in Figure 5.9.1. The major challenge lies in designing an amplifier which must be stable for every position of switch. Moreover, due to inclusion of the switch, the phase of both the arms must be adjusted to minimize the loss due to phase imbalance.

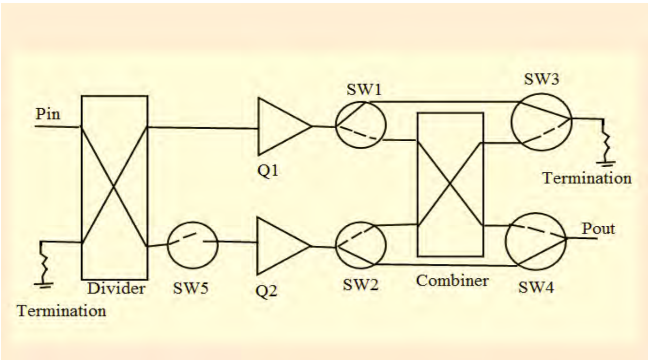


Figure 5.9.1: Proposed Balanced Configuration for GaN

5.10 Adaptive Temperature Compensation technique to improve the Gain and Output Power variation over temperature:

The satellite base plate temperature varies between -10 ˚C to +60 ˚C, so it is a great design challenge for active sub-system designers to maintain it's stable performance over such large range so that user services are not affected much. This requires a precise technique, called temperature compensation technique to maintain all important parameters like gain, Noise Figure, Inter Modulation Distortion, output power etc., within specified limits. Out of all other parameters, gain and output power of the payload are more important determining satellite transmit EIRP, are defined as major specifications known as Gain Stability and EIRP stability. Typically, the specified value for transponder Gain stability is 2 dB peak to peak maximum and EIRP stability is 1 dB peak to peak maximum over the temperature range from -10 ˚C to +60 ˚C. Both these parameters are mainly determined by SSPA, so more accurate compensation of SSPA is mandatory. As compared to the other sub-systems, SSPA is a non-linear sub-system and always operated in saturation so its output power variation is also a non-linear function of temperature. Moreover, the variation of all other preceding subsystems has to be absorbed by SSPA so temperature compensation of SSPA is very complex and time consuming process.

The SSPA is designed using 8 to 9 stages in cascade to achieve the required gain of about 80 to 90 dB. For each active device, the gain variation is about 0.015 dB/ ˚C so the overall gain variation is 8 to 10 dB over the temperature extremes of -10 ˚C to +60 ˚C. Ideally, there should be no variation but efforts are put to minimize it so that overall specification is met. For example, the overall output power variation of 8 dB can be reduced to 1 dB using Microsoft excel calculations, the variation can be brought within 0.8 dB. When all sub-systems (Receiver, Convertor, Modulator, power supplies, SSPA etc.) are cascaded in the payload, the overall variation becomes still larger resulting in large variation of RF output power and hence the satellite transmit EIRP.

In general, the output power decreases in Hot (+60 ˚C) and increases in cold (-10 ˚C). Using standard temperature compensation circuit, as explained below, it is not very difficult to reduce the power in cold but it is very difficult to increase the power in hot as the permitted level of compression is fixed and device's sourcing capacity is also fixed.

For 100 Watt SSPA, the minimum RF output power required is +50 dBm (100 Watt) under all operating condition so to achieve this level at +60˚C temperature, the SSPA is designed to deliver +50.5 dBm at ambient (+25 ˚C). When SSPA is cascaded with other sub-systems, which also follow the same trend in hot temperature, the output power reduces further. So to meet the specification of +50 dBm (minimum), the power at ambient is kept still higher, typically +50.7 dBm. Thus, to meet the EIRP specification at EOL, the SSPA is designed with higher output power, which consumes higher DC power resulting in reduced efficiency.

So far no efforts are put to make corrections after the launching of satellite. A novel scheme is presented which helps to make correction in the EIRP variation.

Besides this drawback, another issue lies in meeting the specification of gain and output power variation over the temperature limit. For each active subsystem designer, the most difficult and time consuming task is to meet the specifications over the specified operating temperature range. The designer has to test each subsystem in thermal chamber, to achieve the required performance, which is tedious, time consuming and costly measure, especially for time bound projects. Even after such efforts, the overall performance of all these cascaded subsystems in satellite thermo vacuum test crosses the specified limit in most cases. At this stage, it is not possible to make any correction so to meet the specification, more margins are kept in the payload design which is non-optimum. These two problems can be solved using a novel technique called adaptive temperature compensation technique. Figure 5.10 shows a conventional temperature compensation network used in most of the active subsystems.

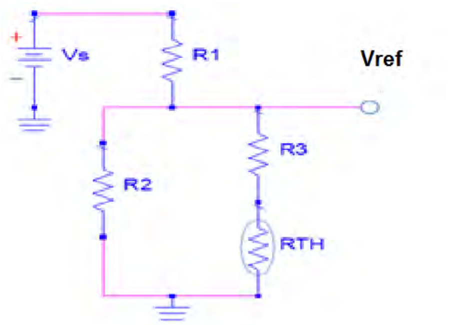


Figure 5.10: Conventional Temperature Compensation Technique

A voltage divider network is used to generate reference voltage V_{ref} to change the bias of the PIN diode circuit. The PIN diode attenuator is designed using a Lange Coupler and PIN diodes, which can provide or release necessary attenuation in the RF path [14]. The PIN diode works as a linear resistor at microwave frequency, whose resistance varies with DC bias current [15]. Vs is the constant voltage coming from the regulator and R_{th} is the temperature sensing resistor called thermistor. The thermistor exhibits non-linear resistance changing with temperature but for a small specified range it is possible to obtain a fairly linear relationship. A series and a parallel resistor when added to this thermistor can vary the resistance in accordance with the temperature. Figure. 5.10 shows a voltage divider network including a thermistor for providing the required reference voltage. The reference voltage should be changed to keep the gain and power of the active subsystem constant with changing temperature. The reference voltage is a function of the base plate temperature.

The reference voltage V_{ref} can be obtained from the network as per equation below:

$$V_{ref} = V_s[\{(R_3 + R_{TH})||R_2\}/\{R_1 + (R_3 + R_{TH})||R_2\}] \qquad (3)$$

The above equation can be re-written in the following form

$$V_{ref} = V_s\left[\left\{\frac{R_2}{(R_1+R_2)}\right\}R_{TH} + \{\frac{R_3R_2}{(R_1+R_2)}\right] / \left[R_{TH} + \{\frac{(R_1R_2+R_2R_3+R_1R_3)}{(R_1+R_2)}\}\right] \quad (4)$$

In order to find out three resistors, different reference voltages required for PIN diode to provide attenuation over the specified temperature range of -10 ˚C to 60 ˚C. are obtained such that the gain of the device should remain constant over this specific temperature.

Thus, by solving (4) for the three unknowns viz. R1, R2 & R3, the required reference voltage can be obtained. A simple calculator can be programmed in MS-Excel or MATLAB and by varying R1, R2 & R3, reference voltage behavior can be obtained easily as per requirement and availability of resistors.

In order to fine tune the required gain and power variation over the temperature range, any of these three resistors are changed, but it is possible only before the cover closing of the subsystem.

A novel scheme is proposed using which, it is possible to change the slope of the compensation curve. Using this concept, it is to compensate the subsystem over the narrow range rather than wide range of temperature from -10 ˚C to 60 ˚C. The proposed concept of using real time base plate temperature above, can be applied and the compensation should be done only for narrow range of temperature. This will result in improvement in efficiency, reduced efforts of the subsystem designer and cost of the hardware.

The reference voltage applied to PIN diode can be changed remotely using the telecommand attenuator circuit presented in section 5.7, figure 5.7.1. The required voltage can be generated using telecommand from ground as per the Table 5.1.7, which can be added or subtracted with the reference voltage. It is possible to overcompensate or undercompensate the SSPA so as to achieve the required variation.

5.11 Conclusion

As seen from the results, the flexible thermal management technique results in saving of a remarkable amount of DC power as well as reduction in power dissipation as heat especially for space segment. Using the adaptive temperature compensation technique, it is possible to compensate the SSPA over narrow range of temperature and also to improve the variation of output power and gain over the operating temperature range. This will result in improvement of efficiency, satellite thermal management, saving in the cost of on-board DC power generation and also the launching cost of geostationary satellite. This will help the SSPA manufacturers to replace the TWTAs by Solid State Power Amplifiers resulting in a tremendous saving in mass, volume and cost for spacecraft manufacturers. This is the simplest way of providing the flexibility for thermal management and to the best of our knowledge such technique has not been reported so far.

REFERENCES:

[1] Electronic De-rating for Optimum Performance, Reliability Analysis Center under contract to Defense Center Columbus (DSCC), p104 (2000)

[2] JPL De-rating GuidelinesJPL-D-8545 Revision D, Jet Propulsion Laboratory under contract to National Aeronautics and Space Administration (NASA), pp 14-15 (2003)

[3] R. Doshi, Deepak G., D. Singh, D. Das, "Flexible Solid State Power Amplifiers for Space use", International Journal of Microwave and Optical Technology, Vol.10, No.2, March 2016 pp 126-131

[4] N. Font, C. Bloss, P. Lautier, A. Barthere, P. Voisin, "Flexible Payloads for Telecommunication Satellites, a Thales Alenea Space perspective", 32nd AIAA International Communications Satellite System Conference AIAA 2014-4382

[5] Ding, Yigang, Weiquan Feng, and Dekui Yan, "Degradation of optical-properties of thermal control coatings under space low energy electrons."Proc. 11th International Symposium On Materials in a Space Environment, 2009

[6] H. S. V. Murthy, A. K, Sharma, K. Badrinarayana, Lakshminarasimhan, "Thermal Management of GEO Satellite Communications Payloads", Vacuum Electronics Conference (TVEC), 2011 IEEE International, Bangalore, 2011, pp. 469-470.

[7] N. Sozbir, M. Bulut, M. F. Oktem, A. Kahriman, A. Chaix, "Design of Thermal Control Subsystem for TUSAT Telecommunication Satellite", World Academy of Science, Engineering and Technology 43, 2008

[8] Townsend, J., Powers, C., Vinens, M., Ayres-Treusdell, M., and Munoz, B., "Degradation of Teflon FEP Following Charged Particle Radiations and Rapid Thermal Cycling" in Proceedings of the 20th Space Simulation Conference: The Changing Testing Paradigm, National Aeronautics and Space Administration, CR-1998-208598, October 1998, pp 201-209

[9] S. Kalyani, G. Ponchak, R. Shaw, "GaAs MMIC Reliability Assurance Guidelines for Space Applications", JPL Publication 96-25, Jet Propulsion Laboratory, December 1996.

[10] Electronics De-rating for optimum performance, Reliability Analysis Center under contract to Defense Supply Center Columbus (DSCC), p106(2006)

[11] Gilmore, David. G, "Spacecraft Thermal Control Handbook", AIAA pp 527

[12] Ramesh Doshi, Prateek Bansal, Nishant Jaiswal, D R Prajapati, Bijeev N, P S Bhardhwaj, Virender Kumar, Surrenders Singh, "Challenges in 100 Watt UHF SSPA for Communications

Payload" International Conference on Engineering, NUiCONE-2013, 28-30 November, 201373
[13] Keya Shukla, N.V. Bijeev, Virender Kumar, Praveen Bhardhwaj, Amit Bhatt, Ramesh Doshi, "EPC with Dynamic Bias Control for SSPA for Space Applications" International conference on Advances in Power Conversion and Energy Technologies, APCET
[14] S. C. Bera, R. V. Singh and V. K. Garg, "Driver circuits for temperature-invariant performance of junction diodes," in *IET Circuits, Devices & Systems*, vol. 3, no. 4, pp. 143-152, August 2009. doi: 10.1049/iet-cds.2008.0266
[15] Robert H Caverly and Shariar Khan, "Electro thermal Modelling of Microwave and RF PIN Diode Switch and Attenuator Circuits".

CHAPTER 6
Efficiency Improvement Technique of SSPA under multi-carrier operation for Geo Synchronous Satellites

6.0 Objective:

The SSPA or TWTA is the non-linear sub-system operating at saturation in the communication transponder so contribute to the overall non-linearity of the satellite communication system. All the transponders are operated under the multi-carrier operation, which generate higher order inter modulation product, in which the third order product are prominent. Accurate measurement of the third order inter modulation product is necessary to achieve the most optimal performance of the transponder. The objective of this research is to provide an accurate and repetitive measurement of third order inter modulation product so that the SSPA can be operated in the saturation region otherwise its' efficiency will be degraded.

6.1 Introduction:

The communication satellite requires SSPA and/or Travelling Wave Tube Amplifiers (TWTA) for RF power amplification to meet the required Effective Isotropic Radiated Power (EIRP) specification for transponder. The input fed to the power amplification units is generally digitally modulated. Also multiple such carriers are amplified simultaneously through a single amplifier to derive the best possible utilization of space hardware, payload mass and available DC power and termed as Frequency Division Multiple Access (FDMA).

The SSPAs and TWTAs are generally operated in saturation for single carrier operation to derive trade-off between output power, efficiency and linearity. However, in multi-carrier operation, the amplifiers are operated in back-off

The earth station also has non-linear power amplifier and with FDMA, multiple carriers are applied to its input [1]. The effect of multiple carriers in the non-linear circuits is well explained in [2-3]. Pedro in [2] states that for an input having equally distant K tones applied to non-linear systems will have output given by

$$\begin{aligned} y_n(t) &= \frac{1}{2^n}\sum_{k_1=-K}^{K},\ldots,\sum_{k_n=-K}^{K},\ldots,X_{k_1}\ldots X_{k_n}H_n\left(\omega_{k_1},\ldots\omega_{k_n}\right)\times \\ &\exp[\left(j\{\omega_{k_1}+\ldots+\omega_n\right)t+\phi_1+\ldots+\phi_n\}] \end{aligned} \tag{1}$$

Thus the output spectrum will be a set of equally separated original frequencies as well as linear combination of the same having amplitude proportional to the coefficient

$$t_n = \frac{n!}{m_{-k}!...m_{-1}!\, m_1!...m_k!} \qquad (2)$$

Where n is the order, m_k are the positive or null integers representing the number of times the selected frequency is present in the required combination product.

These linear combination products are called as inter modulation products. The odd order products, especially third order (for a two carrier case), (*2f2-f1, 2f1-f2*) and to a lesser extent the fifth order products (for a two carrier case) (*3f2-2f1,3f1-2f2*), where *f1* & *f2* are the input frequency components, become significant as they fall in the amplifiers pass band as for a satellite repeater, the center frequency is much larger as compared to its pass bandwidth [1]. These inter modulation products cause loss of power for original carrier frequencies as well as create interference for the adjacent channel and is termed as Adjacent Channel Interference (ACI).

In case of modulated carriers, the power of the inter modulation products is spread over a band of frequencies and with large number of modulated carriers present in the same band, the inter modulation acts as white noise because of superposition of its spectra over the whole bandwidth of the amplifier [1]. This affects the overall station to station carrier power-to-noise power spectral density ratio $(C/No)_T$ of the link as explained in [1] and given by

$$\left(\frac{C}{N_0}\right)_{T^{-1}} = \left(\frac{C}{N_0}\right)_{U^{-1}} + \left(\frac{C}{N_0}\right)_{D^{-1}} + \left(\frac{C}{N_0}\right)_{I^{-1}} + \left(\frac{C}{N_0}\right)_{IM^{-1}} \left(Hz^{-1}\right) \qquad (3)$$

Where, $(C/No)_U$ and $(C/No)_D$ are values of for the uplink and downlink when the satellite channel is operated at certain input power, $(C/No)_I$ is due to interference noise and $(C/No)_{IM}$ is due to inter modulation noise generated both in transmitting earth station and the transponder.

Thus, it can be seen that the available output power of the amplifier is shared between the carrier power, the thermal noise and inter modulation noise. It can also be seen from Fig 7.1, the value of $(C/No)_T$ is maximum at certain input back-off, thereby forcing the system designers to operate the amplifiers at certain input back-off conditions. This in turn reduces the total power available for channel due to back-off and RF power per carrier during multicarrier operation. Thus to make a trade-off between output power, efficiency and overall carrier to noise ratio is a great challenge for SSPA designer.

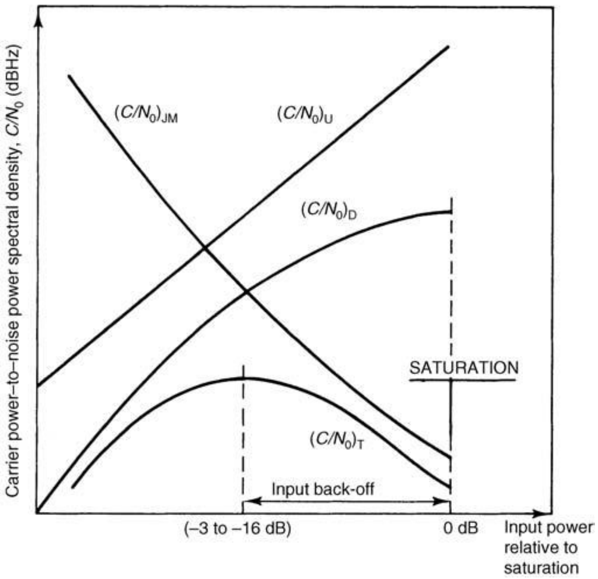


Figure 6.1: Carrier power-to-noise power spectral density ratio versus input power

As seen from the above explanation, it becomes important to properly characterize the amplifier in multicarrier operation mode for Inter Modulation Distortion (IMD), especially for modulated carrier, as the overall efficiency of the satellite communication channel in FDMA mode, the space hardware and launch cost optimization depends upon it. This paper presents a method used for characterizing a 100W UHF Band SSPA [4] for QPSK modulated multicarrier excitation.

6.2 Challenges in Multicarrier operation of SSPA:

Using theoretical calculations, the frequency and level of inter modulation products generated under the multicarrier operation can be easily derived but an accurate measurement of inter modulation product under the multicarrier is indeed a challenging task for the sub-system designer. To measure IMD under five tone signals, one has to arrange five different signal sources, combine all them using suitable combiner and then equalize all them to same level before feeding to an amplifier. This is a complicated and erroneous measurement setup. In most of the cases, the measurement for third order inter modulation distortion (IM3) is made for two tones only where phase adjustment do not matter, but this was for the first time for us to measure five tone IM3. So in order to have an accurate measurement it is necessary to have single instrument generating equal tones at different frequencies. Agilent's Vector Signal Generator (VSG) has the capability to do this type of measurement accurately. The IMD measurement of the SSPA is important to ensure the in-band distortion or carrier-to-inter modulation levels for the transponder. When multiple tones of equal amplitude and random phase are applied to the amplifier, the instantaneous maximum power is achieved. The Peak

Envelope Power (PEP) or the instantaneous maximum power of all the tones is explained in [5]. For N tones each of the peak voltage V_1 at the load, the PEP will be

$$PEP = \left(\frac{(V_1 \cdot N)^\wedge 2}{2R}\right) = N^\wedge 2 \cdot P_i \qquad (4)$$

Where, N is the number of tones and P_i is the input power of each tone.

However, with the randomly varying phases, the total power is not constant but varies between a certain limit. In general, it is indicated in terms of Peak-to-Average Power Ratio (PAPR). The simple case for a two tone signal is explained in [6]. An input signal consisting of two sinusoids frequencies *f1* and *f2* and amplitude A can be represented by

$$X_{input}(t) = A \cdot Cos(2\pi f_a)Cos(2\pi f_b) \qquad (5)$$

$$\text{Where} \quad f_a = \frac{(f_1 + f_2)}{2} \;\&\; f_b = \frac{\mathrm{mod}(f_1 - f_2)}{2}$$

Thus it can be derived from (4) that the Peak Envelope Power (PEP) for a two tone signal is four times the level of individual carriers or the Peak-to-average Power ratio is 3dB. [2] further explains that extending the above case for multiple or n-tones results in

$$Peak - to - Average - power = 10 \cdot \log_{10}(n) \qquad (6)$$

Thus from (3) and (5) it can be concluded that the absolute maximum power is governed by the number of input carriers but the Peak-to-average Power ratio and its probability distribution depends upon the variability of phase of each carrier or in turn the type of modulation of the input carriers.

This phenomenon with the multicarrier transmission is a challenge for the SSPA and Electronic Power Conditioner (EPC) designer. The QPSK modulation is a constant Envelope Modulation however in case of equally spaced multiple QPSK modulated carriers, the envelope power of the combiner input signal varies. Thus when this signal is applied to the input of a SSPA, the DC current requirement also follows the input envelope thus peaking during the PEP and varying as Peak-to-average power requirement. Thus EPC designers have to regulate the EPC outputs for a broader dynamic range. Also, safeguard is required against false tripping provided as a safety feature in EPCs for overload conditions. For space applications as the sub-systems are non-repairable, even a false tripping due to such safety feature has to be justified at various review forums and if such safety features are not provided, catastrophic failures may not occur but later it may degrade the reliability if overstressed.

Another challenge faced is the multicarrier inter modulation performance of the amplifier due to this large variation of the envelope power. This is of concern to the system designer as the interference and noise increases intermittently thereby degrading the overall performance of the transponder.

In case of the 100W UHF SSPA, with five QPSK modulated tones, the PEP at the output was about 500 W whereas the Peak-to-Average Power Ratio was about 7dB. Hence the secondary current requirement of the EPC was from 3A to 11A approximately. Thus many a times, the false tripping-off behavior was observed. During measurement if all signals are applied with same phase, the IMD generated will be worst case condition and performance will not be met. If random phase signals are applied, in some cases the IMD was better and in some cases it was poor thus the results will not be consistent. As stated above, the variation in inter modulation was also observed. The measured multicarrier carrier-to-inter modulation ratio was from -10dB to -22dB. The analysis and improvement method is presented in next section.

6.3 Test results:

As discussed in the above section, the most challenging task was to achieve the IM3 better than -20 dBc under five tone conditions. The instrument required to measure IM3 under five tone conditions was also not available initially so it was decided to measure two tone IM3 using conventional method. Using the IM3 calculator [7] it was estimated that the specification of -17 dBc IM3 under five tones is equivalent to -20 dBc IM3 under two tone conditions. Later, when the VSG was available, it was found that the measurements were not consistent. The EPCs can be designed with special techniques for the broader dynamic range of current requirement at secondary as presented in [4]. The instantaneous requirement of high current in case of PEP is met be a bank of large value capacitors as 160 µF used in 100W UHF SSPA for multicarrier operation. However, the problem of inter modulation degradation observed in measurement needs understanding in detail.

The PEP is encountered when the phases of all the equidistant tones align. So to avoid frequent PEP, the probability of phase aligning needs to be reduced or alternately the frequency separation needs to be made non-uniform thereby altering the phases indirectly

The relation between the instantaneous angular frequency and phase is given by

$$\omega(t) = \frac{d\phi}{dt} \qquad (7)$$

that converts to instantaneous frequency of

$$F(T) = \frac{1}{2\pi}\left(\frac{d\phi}{dt}\right) \qquad (8)$$

Or the phase can be obtained by inverse transformation as

$$\phi(t) = 2\pi \int_{-\infty}^{t} f(T)dT = \phi(0) + 2\pi \int_{0}^{t} f(T)dT \quad (9)$$

In real time scenario of the communication satellites, controlling phase is not possible due to large path length etc. among other factors however; the option of non-uniform frequency separation can be achieved. In the present case of 5 tones for 100W UHF SSPA, even though were generated from the same reference source, but the there is always few Hz difference between them due to non-accuracies in coherency of the reference. This fact itself is helpful in reducing the probability of PEP, thereby improving the multi-tone IMD performance of the transponder. But this fact needs to be accurately verified for the SSPA on the ground for in-orbit performance prediction. So a random frequency separation variation (within +/- 80Hz) from the specified 20KHz was applied using a Vector Signal Generator (VSG) to all the five QPSK modulated tones and applied to the SSPA.

The Intermodulation distortion performance measured for five tones with equal separation is shown in figure 6.3.1 The measured value varied from -21 dBc to -11 dBc depending upon various combination of relative phases applied to each tones from the generator. The problem of inconsistent result of IM3 could be detected only when the EPC got tripped off when all tones were in phase leading to high current demand and in this case the IM3 was only -11 dBc. The only way to move ahead was to use Linearizer. Similar work has been done to achieve similar performance with the help of Linearizer [8-9]. As presented in [8-9] the linearized UHF SSPA for multicarrier mobile communications, five tones IM3 of around -20 dBc at 40 watt RF output power could be achieved using Linearizer. The UHF GaN SSPA developed [10] uses pre-distortion Linearizer to achieve the Adjacent Channel Leakage Ratio (ACLR) of -25 dBc which has its own disadvantages like additional weight, size and gain requirement. A new technique of frequency staggering as explained above was established and could get the similar performance without Linearizer thereby saving mass, volume and gain.

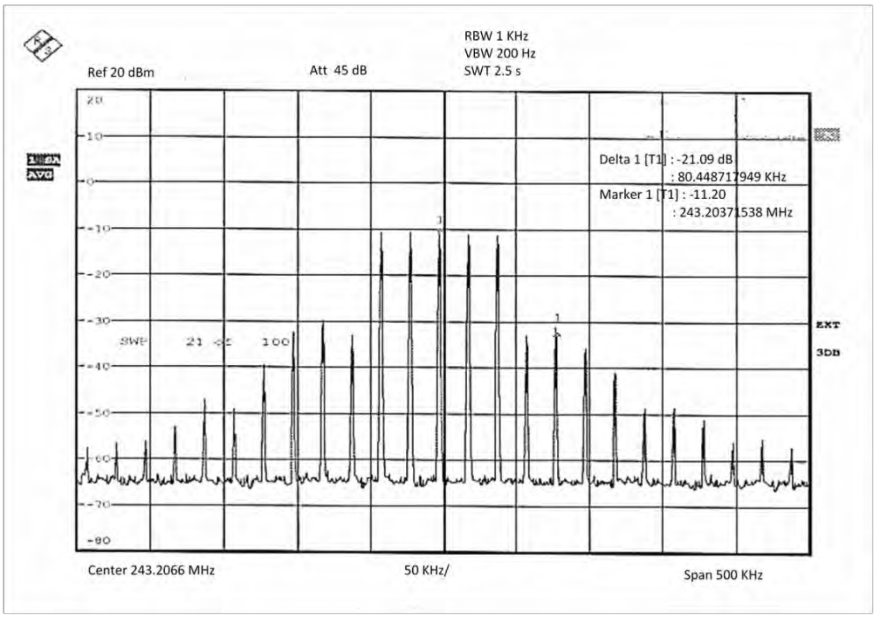


Figure 6.3.1: Intermodulation Distortion performance in best case

These tones were then QPSK modulated using the VSG and applied to the SSPA. Since the phases of the tones continuously vary due to the modulation, Peaks and valleys were encountered as shown in figure 6.3.2.

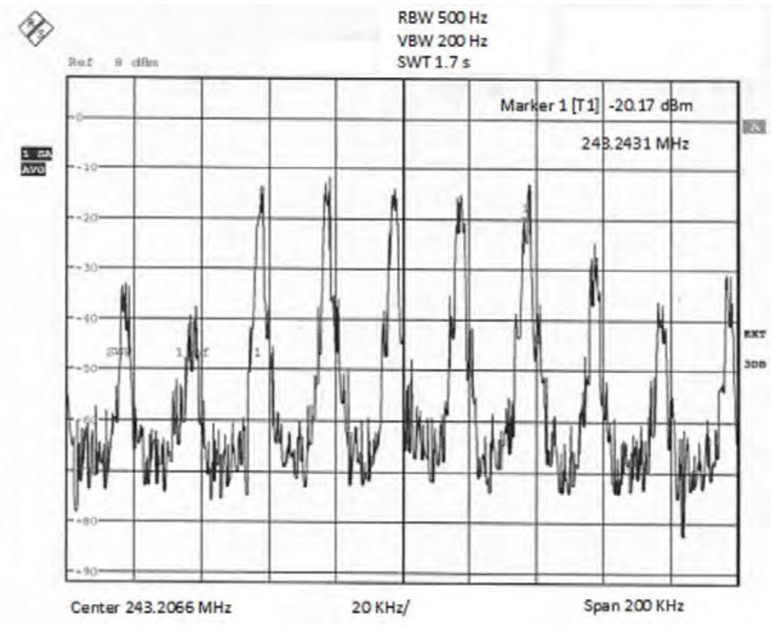


Figure 6.3.2: Intermodulation Distortion performance with QPSK modulation

In order not to allow the peak power to generate, it requires a technique by which the best performance with repetition can be assured. The input spectrum was then modified for unequal frequency separation with random tone spacing within ± 80Hz. As a result, there was reduction in the probability of peaks and valleys. The measured results showed IMD at -19 dBc for 100W output power. These tests were repeated for the acceptance testing of the flight hardware for spacecraft use and consistent results were obtained. Using this technique of frequency staggering, an IM3 of -19 dBc could be achieved. From (3), it can be shown that improvement in IM3 by about 8-9 dB results in an improvement of CNR and hence noise free communication. Moreover, it also results in saving of DC power consumption and thermal dissipation as the SSPA can be operated near saturation.

6.4 Conclusion:

The importance of accurate measurement of multi-tone inter modulation was discussed as it directly affects the FDMA efficiency for the communication channel as well as is a critical parameter to be achieved as a trade-off between output power, efficiency and linearity for the SSPA designer. The paper presented that a practical scenario of minimal unequal separation in the tone frequencies itself helps the designers to achieve better IMD performance of the transponder which otherwise would have been a very challenging task in terms of trade-off for the performance.

REFERENCES:

[1] Gerard Maral, Michel Bousquet," Satellite Communications Systems", 5th edition, John Wiley & Sons Ltd, Chapter 6, 2009.

[2] Jose Carlos Pedro, and Nuno Borges de Carvalho," On the use of multitone techniques for accessing RF components' intermodulation distortion", IEEE Transaction on Microwave Theory and Tecniques, vol.47, No. 12, pp.2393-2402, Dec 1999.

[3] Jose Carlos Pedro, and Nano Borges Carballo," Intermodulation Distortion in Microwave and Wireless Circuits", Artech House, pp. 10-18, 2003.

[4] Doshi, R.; Bansal, P.; Jaiswal, N.; Prajapati, D.R. ; Bijeev, N. ; Bharadhwaj, P.S. ; Kumar, V. ; Singh, S, "Challenges in 100W CW UHF SSPA for communication payloads", Engineering (NUiCONE), 2013 Nirma University International Conference, 2013.

[5] Application Note AN-60-037," High Power Amplifier in Multi-tone Environement", Rev A, Mini-Circuits, 2007.

[6] Mike Geilo," The RF and Microwave Handbook", CRC Press, Chapter 4, 2001.pp. 324-339

[7] http://www.paradisedata.com/files/trnsfr/software/imod_calc.php

[8] http://www.linspacetech.com/PDF/products/UHF_SSPA.pdf

[9] http://www.lintech.com/PDF/UHF GaN Flyer.pdf

[10] A. Katz, B. Eggleston and J. MacDonald, "GaN SSPA for UHF space applications," Microwave Symposium Digest (IMS), 2013 IEEE MTT-S International, Seattle, WA, 2013, pp. 1-4

CHAPTER 7
Reliability Improvement Technique of GaN based SSPA For Geo Synchronous Satellites

7.0 Objective:

The objective of this approach is to improve the reliability of the GaN based for Geo Synchronous satellite so that no surprises are observed once this new technology is launched in the space. Development of Gallium Nitride (GaN) based SSPAs have been reported widely to replace the TWTAs but in absence of sufficient space heritage, failures reported during development and qualification phase of the GaN devices and past experience of GaAs based SSPA failures during 1990's, it is advisable to use a line up using GaAs and GaN devices rather than using all GaN devices in the SSPA. Device level redundancy of GaN along with various techniques such as voltage, current and gain compensation, Automatic level control, dynamic biasing control and different parameter telemetry are proposed. The additional techniques will help to understand any unforeseen failures on-board and also to change over to redundant device with necessary corrections thereby providing uninterrupted services. There will not be any impact on the electrical performance of the SSPA while using such hybrid combination of the devices.

7.1 Introduction:

Microwave Power Amplifiers (PAs) are the most important sub-systems for onboard communications satellites as they consume the highest (80 to 90 %) spacecraft bus power, major contributor to mass budget of payload, determining the non-linearity performance of the payload, the major role player for the spacecraft thermal management and finally the reliability decider of the satellite. The reliability of the spacecraft is mainly determined by thermal management which in turn is dependent on the thermal dissipation so the DC to RF efficiency (power added efficiency) of the amplifier is the prime factor for selection of PA. TWTAs and Solid State Power amplifiers (SSPAs) are two competitors for selection as PAs for space communications payload. Efficiency being the prime requirement, TWTA has been leading the SSPA in competition due to its' higher efficiency even though SSPAs are advantageous in terms of mass, volume, linearity and cost. The main limiting factor for lower efficiency of SSPA is the device's channel temperature which is limited by established de-rating guidelines [1-2]. It is a great challenge for SSPA designers to find out some techniques by which the SSPA performance can be comparable with the TWTA.

TWTA is high frequency, high efficiency, high power amplifier by structure whereas SSPA is solid state device base technology which delivers high RF output power by parallel combination of devices. The device output power is limited by manufacturing process as well as type of the material GaAs or GaN used for its' fabrication. So far many GaAs devices were required to be combined to get higher power so the overall efficiency was degraded. With development of new device technology of GaN, it has now become possible to achieve higher RF output power comparable with TWTA at lower frequencies. GaN has many advantages over the GaAs technology so the future satellite PAs will surely be the GaN based SSPAs. However, being the new technology and no space heritage, the space hardware will demand more redundancy on-board.

For non-repairable space elements, the reliability is more important than the performance or cost. Various studies have been carried out [3-4] to compare both these microwave power amplifiers in respect of their reliability based on in-orbit operating hours' data and found that the failure rate in Failure per billion unit operating hours (FITS) for SSPA's was higher (790 FITs) than the TWTA's (680 FITs). Theoretical calculation of SSPA failure rate number is of the order of 400 FITs, which is far better that TWTAs' number. The reason for higher failure rate of SSPA is due to more number of interconnections, mountings, sensitivity to long term, moderate excursion, thermal cycling etc. but not due to active device failures. This data is for long heritage GaAs based SSPA whereas for newly GaN based the data is not available. Very few vendors have established the reliability data (Mean Time To Failure, MTTF) for GaN technology resulting in far better number (5 FITs) as compared to GaAs technology (20 FITs). The only concern for SSPA designers to use GaN device for long life Geo mission is the failures reported, problems faced during Space Qualification Test (SQT) and absence of no on-board operating data. To overcome such concern, generally the system designers propose more number of the redundant units for new sub-systems like GaN based SSPAs, which will increase the cost of services. A new line-up of the SSPA which will improve the reliability has been presented without not much increase in the cost.

7.2 History and background of SSPA

The SSPA, since its birth in RCA Laboratory is struggling to compete the long heritage TWTA. In 1988, the 4 Watt C-Band TWTAs were replaced by GaAs based SSPAs in many Geo stationary satellites. This achievement was believed to be the end of TWTAs' era. But unfortunately, there were failures observed on board in SSPAs due to use of Aluminum gate structure of GaAs FETs. Metal migration was serious issue due to which many devices failed on board and again the solid state technology was in question. The problem was understood, demonstrated and resolved on ground and hence the aluminum gate was replaced with gold gate. [5]

After thorough investigations of the failure mechanism, it was established that when the final power devices were operated at higher gain compression (3 to 4 dB) the gate metal (Aluminum) diffused into source [5]. Later, the Aluminum gate was replaced with Gold metal and proved to be the right solution to the problem. Since then, the SSPAs with Gold gate GaAs MESFETs are operating satisfactory on board and have successfully replaced TWTAs up to lower power levels of 15 watts at C-and and 40W at L-band. To meet the increasing demand of higher EIRP and higher bandwidth, GaAs MESFET devices were not capable of delivering higher power with higher efficiency amplifier due to their lower drain voltage (lower energy band gap). The approach of combining many devices resulted in poor efficiency so the SSPA technology was again in question. Recent development in GaN Heterojunction FET (HFET) has encouraged the SSPA designers to replace TWTAs for UHF, L, S, C and X Band.

However, before this new technology is used, it is very important to recall the similar event when Si based SSPAs were replaced by GaAs MESFET based SSPAs. The GaAs MESFETs (SSPAs) failed during 1990's which were tested to all extend, were fully qualified and no failure such as metal migration, which occurred on-board was reported during any phase of testing including device level as well as SSPA level qualification on ground. However, after the failure of the GaAs FET devices on-board, many literatures had reported reasons for the failures which raises an alert that sufficient space heritage data, not the accelerated is necessary to establish the reliability for commercial mission. Device manufacturers recommend some parameter for optimum performance of the device but it is also necessary for the SSPA designer to choose the proper value based on the application. For example, the selection of the gate resistance plays very crucial role in determining the reliability. As reported in [5], the SSPA designer is more worried for the device's stability and protection against the overdrive condition so chooses larger value of the gate resistance which helps to reduce the variation in gate current due to change in RF drive level but increases the chance of thermal runaway in the absence of RF drive. Thus any deviation from the accurate value may lead to degradation and hence failure in long duration.

During the period 1991-1995, the satellite communication was not in much demand as compared to the present scenario so the failure of SSPAs did not affect the services so badly that would affect the present services [4]. With this type of experience in past, it is essential to be careful while implementing such new GaN based SSPA for CW application for commercial GEO mission of 15 years.

7.3 Concern About Usage of GaN SSPA-A Literature Survey:

The GaN based SSPAs reported so far [7-13] by various manufacturers are witnessing the forecasted advantages of the wideband GaN material. As mentioned in the state of the art development of GaN SSPA [9], the SSPA has taken over the place of TWTAs up to X band. These are excellent steps towards the replacement of TWTAs but in absence of space heritage data and the failures reported in the GaN devices [14-19] during the development and SQT phases are of great concern from Reliability and Quality Assurance (R & QA) point of view.

As described in [20-22], the industry now takes the reliability of silicon and GaAs transistors for granted, as evidenced by their widespread use in products. This is a result, not only of long standing experience, but also of the development of credible reliability and qualification methodology. Technology is qualified by running standardized stress tests [23-25], and by validating lifetime requirements [26]. This methodology originated from detailed work on the understanding of failure modes, their acceleration and modeling, and a statistical framework to assure a minimum level of quality. The stress tests, however, were developed more than twenty years ago, with the Joint Electron Device Engineering Council (JEDEC) JESD47 document released in 1995 and the Automotive Electronics Council (AEC) founded in 1994. The qualification procedure has remained essentially unchanged over the years, whereas technology and its uses have changed.

Transistors from emerging materials are being judged as “Passing Qual” when run through the standardized stress tests described in [23-24]. For successful technology adoption, it is important to develop credible reliability and qualification methodology. A successful methodology allows the industry to gain confidence that parts will last for the desired lifetime in the end-use application. In order for the industry to develop GaN-specific methodology, it is important to understand the fundamentals and assumptions behind traditional qualification. We agree to the concern raised by [21] and based on the past experience, we do not recommend to use SSPAs with only GaN devices for commercial satellites.

Whenever any new technology is incorporated in long life commercial mission, it is always recommended to provide redundancy so as to attain most reliable services with highest availability [25]. But in the case of GaN SSPA to provide redundancy with the same kind will not serve the purpose. Another way is to use TWTAs as redundant unit for GaN SSPA which is reliable but very costly solution. We propose a scheme which is the most reliable and most economical as compared to other schemes.

7.4 Proposed SSPA

The GaN SSPAs demonstrated so far use only newly developed GaN devices in cascaded chain in their line up so any unforeseen failure of any of the device on-board will lead to total loss of the communication link. So such line up cannot be considered as the optimal approach for long life mission. Hence, we recommend a new hybrid approach that use old (GaAs) and new (GaN) technologies to build the highest confidence and provide best reliability. We propose a lineup that use GaAs MESFETs as driver stages for the GaN HEMT power device and the GaN devices are in the redundant configuration. GaAs MESFET technology has now fully matured and devices capable of delivering RF power level up to 43 dBm (20 Watt) with long space heritage are available from many manufacturers. Similarly, RF MOSFETs are also available up to 100 Watt power level with long space heritage. GaN Devices capable of delivering higher power levels of the order of 100 Watt at C-band, 150 Watts at L and S band and 100 Watt at UHF band are available with power gain of the order of 15 dB. These GaN devices will require driver stages with RF output power of the order of 36-40 dBm (4 Watt to 10 Watt) which are available from many venders with long space heritage. So, it is recommended to use GaAs FET devices up to 40 dBm and to use final high power stage devices with redundancy. The GaAs line up will be housed in a separate package called Medium Power Amplifier (MPA) and the GaN device will be housed in another package called High Power Amplifier. Rather than providing the redundancy at sub-system (SSPA) level, providing the redundancy at the final power device level will result in saving of cost, mass and volume. A coaxial Single Pole Double Throw (SPDT) switch will be at the output of the MPA which will be normally connected with the Main chain of the final power GaN device. Initially only one device (main) will be in operation and if any anomaly or observation occurs, the switch will be operated to change over to redundant device after thorough investigation of the anomaly occurred with the help of various Telemetries provided on-board in HPA. Major concern for high power devices is the thermal issues due to which their reliability and hence life reduces. The device level redundancy will help to improve the reliability of the device by using each device for half the total life if some degradation related to thermal is observed.

During the development phase of GaN device, following major failures were reported.

(1) Current collapse (Dispersion of Drain Current due to increased dynamic ON resistance)

(2) Increase of gate current (Thermionic field emission)

(3) Memory effects (The drain current and gain drops at low power level as well as middle power level so the transfer characteristic deviates from its original behavior)

(4) Field related failure, when submitted to high drain voltage (in the OFF state), the transistor can show catastrophic failure- a recent report [16]

The device manufacturers have attempted to eliminate these effects by changing doping levels and physical properties at device level but in absence of any space heritage data, it is better to provide additional circuitry in the SSPAs which can take help to modify the operating condition of the device. The development on GaN SSPAs reported so far [6-13] represents performance summary only and do not discuss about the provision of additional features to cater to any anomaly or observation. Moreover, no details of SSPA performance under the multi carrier operation and unwanted overdrive condition which is the most likely event for on-board application is given in the reported work. Under the overdrive condition, the SSPA demands higher power from Electronic Power Conditioner (EPC), so an appropriate control circuit has to be provided. The authors [9-10] have presented some details on thermal analysis but it is difficult to understand how a large amount (more than 300 Watt) of power will be dissipated in a small area (300 mm x 245 mm) on satellite panel. As RF unit and EPC are accommodated in a single package so the heat pipe layout may not be feasible. This may be true for positioning satellite where only two to three channels are used but for communication payloads, the number of channels (up to C Band) is 10 to 12 so it will be very difficult to manage the large amount of heat flux density so it is necessary to provide effective heat pipe layout. An additional area may be required for the driver (channel) amplifier unit which is not shown or discussed in the work.

It is always preferred to have compact size and weight for space hardware but for new sub-system like GaN SSPA, performance and reliability are more important than size and weight. So we propose SSPA with three different units viz. HPA, Channel amplifier (CA) stacked on MPA and an associated EPC. These three units are mounted on the satellite panel with embedded heat pipes in such a way that the heat dissipating devices are sitting on the heat pipes for efficient heat transfer [26]. The channel amplifier, MPA and EPC are heritage designs with proven technology so the designer more concern about the HPA only.

Based on the failures reported in GaN devices as listed above and the past experience of failure of GaAs FETs, it is recommended to implement various techniques such as Automatic Level Control (ALC) mechanism, gate and drain current compensation technique, output power and temperature monitoring telemetry and dynamic biasing technique for controlling the voltage and current of the high power devices (GaN). These techniques will help to understand the behavior of the GaN device under different operating conditions on-board, to investigate the failure, if any and to modify the operating condition. All these techniques have been already demonstrated in the work reported in [26-27].

7.5 C Band 100 Watt (CW) SSPA:

We propose C-Band 100 Watt (CW) GaAs GaN SSPA with above mentioned techniques for Fixed Satellite Services (FSS) of Geo Stationary satellite. So far 15 Watt SSPAs and 63 Watt TWTAs have been used in the Normal C-Band for FSS based on the coverage requirement. MELOS developed 70 Watt C-Band GaN SSPA for using all GaN devices [28] but they have not provided any such redundancy and provision to meet the techniques such as described above.

Similar performance can be achieved using combined device type of GaAs and GaN in addition to achieve highest reliability. Later, once sufficient reliability data is gathered the SSPA with all GaN devices can be used for such application. Fig.7.5.1 shows the typical line up of C-Band 100 watt SSPA.

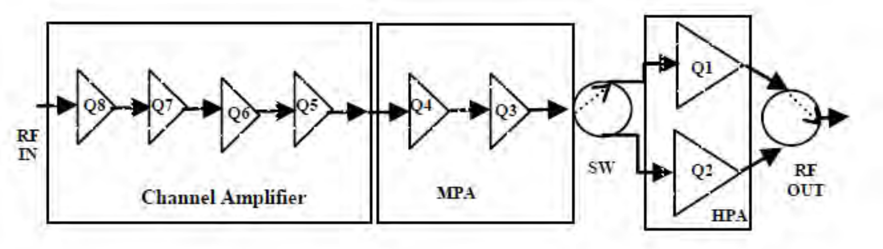


FIGURE.7.5.1: C-BAND 100 WATT SSPA LINE UP USING GAAS PLUS GAN DEVICES

As shown in the line-up, the SSPA is realized in three different packages, viz; CA, MPA and HPA.

This is the most simplified and most reliable line up as compared to those presented so far as the CA (GaAs devices Q5 to Q8) and MPA (GaAs devices Q3 and Q4) are readily available heritage designs so are of no concern and hence the SSPA designer has to concentrate only on HPA (GaN devices Q1 and Q2) along with additional circuitry. This concept of three independent packages with individual specifications helps to expedite the project delivery schedule as the CA and MPA can be kept ready till the GaN devices are received. This is because the GaN devices are not in production line so take longer time to get delivery. The GaN power devices are available with internal matching over wide band so the only challenge lies in the proper optimization of the device for RF output power, linearity and efficiency.

The following features will improve the reliability of the SSPA. These are also the major challenging tasks involved in the realization of HPA.

(1) In the output matching network, 30 dB coupler and detector diode circuit provides RF output power telemetry using which the health of the final device as well as overdrive can be monitored.

(2) Similar circuitry has been provided in the output section of MPA along with comparator and level control circuit which protects the final power device in HPA being overdriven into higher gain compression and hence it's reliability is ensured.

(3) The failure mechanisms such as Drain current collapse and increase of Gate current can be controlled by means of current compensation technique which has been implemented in 100 Watt UHF SSPA [26] as well as changing the gate and drain voltages by means of dynamic biasing technique [27], if required.

(4) In case of memory effect, it is necessary to operate the devices beyond the affected range using dynamic biasing technique [27] as well as gain compensation technique can be provided.

(5) The recently reported field related failure due to high drain voltage (in the OFF state) can be controlled by changing the drain voltage. This has been achieved by dynamic bias control [27].

(6) In order to meet the requirement of multicarrier operation, high value of multilayer capacitors have been provided to cater to the instantaneous peak current.

(7) The output section of the GaN amplifier has to be realized in 50 mil Alumina substrate to handle higher power which is a new design as compared to 25 mil Alumina substrate used so far.

Above all techniques will improve the reliability of the SSPA without increasing much cost.

7.6 Test Results:

As described in the previous section, the CA and MPA being the heritage design, their results are not presented here. The design of final power device is important so the test result of only final power device (C-Band 100 Watt GaN HFET in this case) is presented here. The achieved performance is shown in Table 7.6.1.

Parameter	Targeted Specs	achieved performance
Frequency	3700-4000 MHz	3700-4000 MHz
Gain @ 2 dB GCP	13 dB	13 dB
P_{out} @ 2 dB GCP	50 dBm	50 dBm
DC power	6.0 A @ 28 Volts	6.5 A @ 28 Volts
T_{ch} ˚C (max)	160 ˚C	152 ˚C
PAE	60 %	55 %

Table7.6.1: Measured Results of 100 Watt Amplifier Module

The DC power required by the remaining stages is approximately 30 Watt for either GaN or GaAs line up so the overall efficiency of the SSPA is not affected.

One argument exists regarding requirement of the multiple voltages from EPC if GaAs (8 volt) and GaN (28/50 volt) devices are combined as this degrades the efficiency of EPC. But when the GaN device is operated as a driver stage to the final stage, it's voltage must be lowered otherwise under the overdrive condition, the driver stages will continue to draw more current from EPC and drive the final stage device into harder compression. Thus GaAs device is the right choice when operated as driver stages.

The overall efficiency of the SSPA including the EPC will be around 47% which is still lower than that of the TWTAs (55%) but the other advantages like saving of weight and volume, improved linearity will surely help the SSPA designers to replace the TWTAs for future missions. Similar approach can be applied to new development of GaN SSPAs for different frequencies like UHF band (100 watt), L-band (150 watt) and S-band (250 watt).

7.7 Conclusion

A novel approach of high power SSPA using combination of long heritage GaAs MESFETs and transistor using emerging GaN material has been presented. Rather than providing sub-system level redundancy, the device level redundancy has been presented for the first time. This approach will help to improve the reliability of the SSPA and will also increase the confidence level for replacement of TWTA. Additional features implemented in HPA will help to understand the performance in the GaN in space environment and will also help to cater to any unforeseen failure of GaN device by switching to redundant unit so the services will not be affected. Once sufficient data is archived, the SSPAs with all GaN devices should be used for future missions.

REFERENCES:

[1] Electronic De-rating for Optimum Performance, Reliability Analysis Center under contract to Defense Center Columbus (DSCC), p104 (2000)

[2] JPL De-rating Guidelines JPL-D-8545 Revision D, Jet Propulsion Laboratory under contract to National Aeronautics and Space Administration (NASA), pp 14-15 (2003)

[3] E. F. Nicol, B. J. Mangus, J. R. Grebliunas, K. Woolrich and J. R. Schirmer, "TWTA versus SSPA: A comparison update of the Boeing satellite fleet on-orbit reliability," Vacuum Electronics Conference (IVEC), 2013 IEEE 14th International, Paris, 2013, pp. 1-2. doi: 10.1109/IVEC.2013.6571087

[4] R. Strauss, "Reliability of SSPA's and TWTA's," in IEEE Transactions on Electron Devices, vol. 41, no. 4, pp. 625-626, Apr 1994. doi: 10.1109/16.278524

[5] Internal Report, "Report Of The Committee on SSPAs Anomalies". Space Applications Centre, Ahmedabad. May, 1996

[6] Constantin, Nicolas & Ghannouchi, Fadhel M (1995-12-01). GaAs FET's gate current behavior and its effects on RF performance and reliability in SSPA's. (field-effect transistors) (Special Issue on 1995 International Microwave Symposium). In IEEE Transactions on Microwave Theory and Techniques. v43 (n12), p2918(8).

[7] Kazuhiro Kanto, Akihiro Satomi, Yasuaki Asahi, Yasushi Kashiwabara, Keiichi Matsushita and Kazutaka Takagi, "An X-band 250W solid-state power amplifier using GaN power HEMTs," 2008 IEEE Radio and Wireless Symposium, Orlando, FL, 2008, pp. 77-80. doi: 10.1109/RWS.2008.4463432

[8] K. Nakade, K. Seino, A. Tsuchiko and J. Kanaya, "Development of 150W S-band GaN solid state power amplifier for satellite use," 2010 Asia-Pacific Microwave Conference, Yokohama, 2010, pp. 127-130.

[9] M. Casto et al., "100W X-band GaN SSPA for medium power TWTA replacement," WAMICON 2011 Conference Proceedings, Clearwater Beach, FL, 2011, pp. 1-4. doi: 10.1109/WAMICON.2011.5872886

[10] R. Giofrè, P. Colantonio, L. Gonzalez, L. Cabria and F. De Arriba, "A 300W complete GaN solid state power amplifier for positioning system satellite payloads," 2016 IEEE MTT-S International Microwave Symposium (IMS), San Francisco, CA, 2016, pp. 1-3. doi: 10.1109/MWSYM.2016.7540096

[11] R. Giofré et al., "A first step towards a 230W SSPA for Galileo System exploiting European GaN technology," 2015 European Microwave Conference (EuMC), Paris, 2015,pp.1168-1171.doi: 10.1109/EuMC.2015.7345976

[12] M. Casto et al., "100W X-band GaN SSPA for medium power TWTA replacement," WAMICON 2011 Conference Proceedings, Clearwater Beach, FL, 2011, pp. 1-4. doi: 10.1109/WAMICON.2011.5872886

[13] K. W. Kim, J. Y. Kwack and S. Cho, "1kW Solid State Power Amplifier for L-band radar system," 2011 3rd International Asia-Pacific Conference on Synthetic Aperture Radar (APSAR), Seoul, 2011, pp. 1-4.

[14] C. Unger, M. Mocanul, M. Pfost, P. Waltereit and R. Reiner, "Experimental analysis of the gate-leakage-induced failure mechanism in GaN HEMTs," 2016 International Semiconductor Conference (CAS), Sinaia, 2016, pp. 127-130. doi: 10.1109/SMICND.2016.7783060

[15] E. Zanoni et al., "Reliability of Gallium Nitride microwave transistors," 2016 21st International Conference on Microwave, Radar and Wireless Communications (MIKON), Krakow, 2016, pp. 1-6. doi: 10.1109/MIKON.2016.7492013

[16] L. Zhou et al., "Investigation on Failure Mechanisms of GaN HEMT Caused by High-Power Microwave (HPM) Pulses," in IEEE Transactions on Electromagnetic Compatibility, vol. 59, no. 3, pp. 902-909, June 2016. doi: 10.1109/TEMC.2016.2628046

[17] A. Chini, V. Di Lecce, F. Fantini, G. Meneghesso and E. Zanoni, "Analysis of GaN HEMT Failure Mechanisms During DC and Large-Signal RF Operation," in IEEE Transactions on Electron Devices, vol. 59, no. 5, pp. 1385-1392, May 2012. doi: 10.1109/TED.2012.2188636

[18] E. Zanoni et. al, “Reliability and failure physics of GaN HEMT, MISHEMT and p-gate HEMTs for power switching applications: Parasitic effects and degradation due to deep level effects and timedependent breakdown phenomena,” Workshop on Wide Bandgap Power Devices and Applications (WiPDA), p. 75, 2015

[19] B. D. Huebschman, F. Crowne, A. M. Darwish, E. A. Viveiros, K. Kingkeo and N. Goldsman, "Identification of Pre-Catastrophic Failure Mechanisms in High Power GaN HEMT," 2011 IEEE Compound Semiconductor Integrated Circuit Symposium (CSICS), Waikoloa, HI, 2011, pp. 1-4. doi: 10.1109/CSICS.2011.6062457

[20] S. R. Bahl, “A comprehensive methodology to qualify the reliability of GaN products,” Texas Instruments whitepaper, available at www.ti.com/lit/slyy070 or at www.ti.com/GaN

[21] S. R. Bahl, D. Ruiz and D. S. Lee, "Product-level reliability of GaN devices," 2016 IEEE International Reliability Physics Symposium (IRPS), Pasadena, CA, 2016, pp. 4A-3-1-4A-3-6. doi: 10.1109/IRPS.2016.7574528

[22] L. Han, Z. Xin and Y. Zhen-kun, "The application analysis of GaN power devices in Radar transmitter," 2009 IET International Radar Conference, Guilin, 2009, pp. 1-5. doi: 10.1049/cp.2009.0317

[23] JEDEC Standard JESD47I, “Stress-Test-Driven Qualification of Integrated Circuits,” July 2012.

[24] AEC-Q101, Rev. D1, “Failure Mechanism based Stress Test Qualification for Discrete Semiconductors in Automotive Applications”, September, 2013.

[25] L. Kuzu, A. F. Yagli, M. Gokten and V. Yanikgonul, "Reliability analysis of TUSAT satellite communication payload," 2012 IEEE First AESS European Conference on Satellite Telecommunications (ESTEL), Rome, 2012, pp. 1-5. doi: 10.1109/ESTEL.2012.6400167

[26] Doshi, R.; Bansal, P.; Jaiswal, N.; Prajapati, D.R.; Bijeev, N.; Bharadhwaj, P.S.; Kumar, V.; Singh, S, “Challenges in 100W CW UHF SSPA for communication payloads”, Engineering (NUiCONE), 2013 Nirma University International Conference, 2013.

[27] R J Doshi, Deepak Ghodgoankar, D K Singh, D K Das, “Flexible Solid State Power Amplifier for Space Use”, International Journal of Microwave and Optical Technology, Vol.10, No.2, March 2015

[28] T. Hirona, A Shibuya, T. Kawabata, M. Kido, K. Yamada, K. Seino, A. Ichikawa, A. Kamikoura, “70 watt C-Band GaN SSPA for Satellite Use”, Proceedings of Asia Pacific Microwave Journal, 2014.

CHAPTER 8
Conclusions and suggestions for future research work

8.1 Conclusions

State of the art adaptive techniques to make the SSPAs flexible and to achieve the remarkable improvement in efficiency for Geo Synchronous Satellites have been presented. It has been demonstrated that the Power Amplifiers used so far for Geo Synchronous satellites were of rigid (fixed) performance and hence were suffering from major drawbacks of stagnant performance and poor efficiency. The efficiency being the prime importance for any communication systems, improvement in efficiency has resulted in saving of DC power generation, thermal dissipation and hence reduction of weight, volume and cost of the equipment. To meet the future demand of low cost satellite service can be achieved by replacing the TWTAs with Adaptive (flexible) SSPAs.

With the flexible output power and flexible frequency techniques, efficiency improvement of the order of 10 % has been achieved. This will help the SSPA to attain the efficiency of the order of 55 %, the value comparable with TWTA and hence SSPA will be able to replace the TWTA for future space technology. Flexible output power SSPA will enable the user to change the output power as per their requirement and hence a large amount power can be saved. Similarly, it will now be possible to change the frequency of operation, and hence the same hardware can be used for new frequency. The results demonstrated are very encouraging and will surely find place in the proposed Generic Flexible Payload by European Space Agency and Astrium or equivalent flexible payload.

The adaptive thermal management technique presented is very useful for future mission as to meet the higher EIRP demand of user requirement, higher power SSPA will be used and thermal management will become very critical. With this novel approach, 7% to 8% efficiency can be improved resulting in considerable amount of DC power saving. With the help of adaptive temperature compensation technique, it will be possible to improve the Gain and EIRP stability even after launch of the satellite.

Lastly, a reliable technique will improve the reliability and efficiency of the amplifying device.

As compared to the conventional fixed performance communication payloads, the flexible payloads will allow the satellite users to use the same hardware as well as update themselves with the rapid changing technology.

The GaN HFETs are proving their confidence in the SSPA designer for long life mission due to their excellent performance so GaN based SSPA will surely replace the old vacuum technology TWTAs not only for space but also for ground base applications. The proposed flexibility at higher frequency and higher power will surely need sufficient care to provide failure safe design of SSPAs for long life mission. Reliability being the prime importance, the efficiency improvement using adaptive technique will result in less DC power generation on-board, less thermal heat dissipation and reduction in weight and size of the payload and finally cheaper satellite communication with state of the art updates.

8.2 Suggestions for future research work

The prime objective of the current research was to design and develop high power adaptive SSPA so the state of the art GaN devices with wide band gap energy were considered. The designs were limited up to C-Band only because these devices were available up to C-Band only. At higher frequency band like Ku-Band (10.7 GHz to 12.2 GHz), the recently reported devices are up to 100 Watt, which is still of lower power as compared to TWTAs (140 Watt). Two such devices can be combined to achieve the required power level and then the adaptive techniques can be implemented in this SSPA. Similarly at Ka-Band (17.5 GHz to 21.5 GHz), depending upon the availability of the device, the adaptive techniques can be used which will find the application in High Throughput Satellite (HTS).

Appendix
Technical Specification of High Power SSPA

While designing the high power SSPA for space applications, it is necessary to understand some important specifications of SSPA in detail. Here all the specifications related to electrical, mechanical, thermal and reliability and quality assurance aspects of a typical 200 Watt SSPA are explained in detail. Also while working for Space applications, many newer specifications need to be considered as compared to ground use.

Sr. No	Parameter	Specifications
1.	Frequency	1.3 GHz
2.	Channel Bandwidth	25 MHz
3.	RF output power (min.)	+53 dBm (200 W) @ 2dB compression
4.	Large signal Gain	83-85 dB
5.	Gain flatness	< 0.2 dB (p-p) over 40 MHz @ 20 W
6.	Phase Shift (max)	22 º
7.	AM/PM Conversion	5 º/dB
8.	TC Attenuator settings	0-24 dB in steps of 2 dB
9.	TC Attenuator setting accuracy	±0.5 dB
10.	Third Order IMD (each carrier input back-off)	-3 dB : -13 dBc
		-10 dB : -20 dBc
		-17 dB : -30 dBc
11.	VSWR (Input & Output)	1.2: 1 max.
12.	Overdrive capability	15 dB for 2 Hours
		10 dB for 24 Hours
13.	Power consumption	< 200 watts
14.	Temperature Range	Non-operating: -40º C to +80º C
		Operating: 0º C to +50º C
		Acceptance: -10º C to +60º C
		Qualification: -15º C to +65º C

Table: 1 Typical Specifications of 200 Watt L Band SSPA

(1) Electrical Specifications:

1. SSPA Constituents:

The SSPA consists of RF low and high Power Amplifiers, Tele-commendable attenuators and Electronic Power Conditioner (EPC) including the Electrical Interface Circuits.

2. RF Power Amplifiers:

These could be low, medium and high power amplifiers. The nominal RF power output of power amplifier (PA) should be 200 Watts (53 dBm) in the specified operating frequency bands.

3. Commendable Attenuator/Gain Setting Circuit:

The Commendable attenuator is used to set transponder gain by ground command. This is accomplished by inserting attenuation into transmission path of each SSPA. Variable Gain Amplifiers could also be used for this purpose.

4. Electronic Power Conditioner:

The EPC has the main function to provide the desired DC voltages to the PA unit from the DC main bus voltage of the spacecraft (26 V - 43 V). The EPC also has to control the switch-on and the switch-off sequence to protect the Amplifying devices from burnout and other damages. It also has to generate the outgoing telemetry signals and has to process the incoming telecommand signals.

5. Operating Frequency Range:

While designing an SSPA we have to specify the usable bandwidth of the SSPA which may be about 200 to 250 MHz depending upon the requirement. The Operating Bandwidth of SSPA is 20 MHz.

6. Output Power

With a single carrier, the rated RF output power should be +53 dBm (200 Watt) minimum at maximum gain compression of 2.0 dB over the operating frequency range at the end of life (EOL).

7. Overdrive Capability

The SSPA should be designed to withstand overdrive levels upto +15 dBm (for 24 hours), without any subsequent degradation in electrical performance or lifetime. The demonstration of overdrive capability is done at minimum gain condition.

8. Impedance

The nominal impedance at the RF input and output ports are 50 Ohms.

9. VSWRs

The input and output VSWRs in non-operating and operating conditions are less than 1.2: 1. The output VSWR measurements for operating conditions are performed keeping the DC ON and RF OFF.

10. Operating Under Different Load Conditions:

The SSPA should meet all requirements when coupled to a source and load having in-band VSWR not exceeding 1.2, any phase and an out-of-band VSWR upto infinity, any phase.

The SSPA should be unconditionally stable and not get damaged if the Output and/or Input ports are terminated by loads having an infinite VSWR, any phase.

11. Large Signal Gain (Single Carrier):

The large signal gain of the SSPA measured at rated 200 Watt output power level is of the order of 84 dB to 87 dB.

12. Small Signal Gain (Single Carrier):

The small signal gain of the SSPA should be measured at 1-Watt output power level and it should be maximum 2.0 dB more than the corresponding large signal gain value.

13. Gain Flatness:

The gain vs. frequency should not exceed the following requirements:

- 0.2 dB p-p (max) over any 20 MHz in the operating frequency band at 200 W output power level (saturation level).
- 0.4 dB p-p (max) over any 40 MHz in the operating frequency band at 1 W output power level (linear).

14. Gain Stability (Short Term):

The short-term stability at any frequency over the operating frequency range shall not exceed

- 0.25 dB p-p for large signal gain (24 hours).
- 0.40 dB p-p for small signal gain (24 hours).

15. Gain Stability (Long Term):

The long term gain stability for large signal should be within –0.32 dB ± 0.74 dB (p-p) (over a period of fifteen years).

16. Phase Shift:

The phase shift, relative to 20 dB below the nominal input drive conditions of any unmodulated carrier, at any point within the operating frequency band and at various power levels shall not exceed the following values:

Input back-off versus Phase Shift (Deg p-p, max)

Input back-off	Phase Shift (Deg p-p, max)
20 dB	0
10 dB	1
6 dB	3
3 dB	10
0 dB	22

17. Third Order Intermodulation Products:

The level of third order intermodulation products of two equal carriers (each 3 dB below the single carrier nominal input level required to drive the SSPA to deliver rated power output) should not exceed values as given in the following table:

Each Carrier back-off relative to single carrier level Third order IMD product level at the output relative to either output carrier level

Each carrier Input back-off	IMD level
-3 dB	-13 dBc
-10 dB	-20 dBc
-17 dB	-30 dBc

This specification should be met with carrier spacing from 500 kHz up to 40 MHz and for all intermodulation products falling into the operating frequency range.

18. Spurious Products:

The SSPA input and output should not exhibit spurious signals (i.e. signals not harmonically related to the input signals), of more than -80 dBc when the amplifier is driven by a single carrier at any level between zero and 200 W output power at any frequency in the operating frequency band.

Spurious in the RF output due to the injected noise should be within –60dBc at Beginning of the Life (BOL).

19. Commendable Gain Setting

It should be possible to reduce the gain of the SSPA by up to 24 dB, in 12 steps of 2 dB each. The accuracy of each Gain setting should be ± 0.5 dB. It should be possible to set the SSPA gain within this 24.0 dB dynamic range by giving a single command from the ground.

(2) Reliability & Quality Assurance (R & QA) Requirements:

Introduction:

Reliability and Quality are important prerequisites of any space program hardware. The hardware placed on the spacecraft is not repairable so sufficient care should be taken for the reliability of each and every component. It is therefore, very essential to understand and implement the R & QA requirements judiciously. This section provides the details of R & QA requirements, which an SSPA has to meet if it wants to sit on the spacecraft.

2.1 Reliability

2.1.1 Life:

- The SSPA should meet all the design requirements for use on-board spacecraft with a minimum life for 15 years.
- The SSPA should be capable of meeting all the functional requirements at various stages of spacecraft assembly and storage as follows:
    - 3 years' storage and life at various levels of spacecraft's assembly.
    - 5 years in controlled environmental conditions.

2.1.2. Environmental Conditions:

The SSPA should be capable of withstanding and performing under following environmental conditions.

2.1.3. Non-Operating Environment:

The units should be capable of withstanding following environmental conditions:

- Temperature Range: -40 ᵒC to +80 ᵒC
- Pressure: Ambient to 10-10 Torre
- Relative Humidity: Upton 95% without condensation of water at +40 ᵒC.

(3) Operating Environment:

3.1. Turn-On

The unit should be capable of being turn ON without any damage at –40ᵒC.

3.2. Temperature Range

- Acceptance Temp. Range: -10 ᵒC to +60 ^{0}C
- Qualification Temp. Range: -15 ^{0}C to +65 ^{0}C

3.3. Pressure

The SSPA should be capable of operating at any pressure between 1 atmosphere and hard vacuum of the order of $1x10^{-10}$ Torr. The design should allow quick depressurization during launch ascent. Venting rate will be 14 mm. of Hg per sec (minimum).

3.4 Vibration

The SSPA should be designed and fabricated to meet the vibration tests (sine and random) as per the test plans.

3.5 Space Radiation

The SSPA should be designed and fabricated to operate without any degradation in performance or life for total radiation dose of 1 x 107 rad.

List of the Journal papers published/submitted:

(1) R J Doshi, Deepak Ghodgaonkar, D K Singh, D K Das, "Flexible Solid State Power Amplifier for Space use." *International Journal of Microwave and Optical Technology,* Vol.10, No.2, pp 126-131, March 2015.

(2) R J Doshi, Deepak Ghodgaonkar, "Adaptive Thermal Management Technique to Improve the Efficiency of SSPA for Geosynchronous Satellite Applications" *Journal of Heat Transfer*, Volume 140, Issue 5, May 2018.

(3) R J Doshi, Deepak Ghodgaonkar, "A novel Technique to Improve the Efficiency of SSPA for Space Applications" Submitted to *International Journal of satellite Communications and Networking* on 15th October, 2016 and re-submitted after reviewer's comment on 20th November, 2017.

(4) R J Doshi, Deepak Ghodgaonkar, "Adaptive Temperature Compensation Techniques for SSPA for Geo Synchronous Satellites" Accepted for publication in *International Journal of Electromagnetics and Application, Scientific and Academic Publishing, USA.*

List of the Conference papers published:

(1) R. J. Doshi and D. Ghodgaonkar, "Techniques to Reduce the Cost of the Satellite Base Solutions," *2017 2nd International Conference on Communication and Electronics Systems (ICCES)*, Coimbatore, India, 2017, pp. 624-628. doi: 10.11 09/CESYS.2017.8321153

(2) R. J. Doshi, D. Ghodgaonkar, V. D. Parekh, A. N. Patil, "High Power Test Set Up: From Trolley to Table Top," *2017 2nd International Conference on Communication and Electronics Systems (ICCES)*, Coimbatore, India, 2017, pp. 687-691. doi: 10.1109/CESY S.2017.8321167

(3) R J Doshi, Deepak Ghodgaonkar, "Reliability Improvement Technique of GaN SSPA for Geo Stationary Satellites", *2017 International Conference on Intelligent Computing, Instrumentation and Control Technologies (ICICICT)*, Kerala State, India, pp. 1390-1394. doi: 10.1109/ICICICT1.2017.8342773

(4) R J Doshi, Deepak Ghodgaonkar, P S Bhardhwaj, D K Singh, D K Das, "Accurate Characterization of High Power SSPA under Multicarrier Operation for Satellite Communications." *2017 International Conference on Intelligent Computing, Instrumentation and Control Technologies (ICICICT),* Kerala State, India, 2017, pp. 818-823 doi: 10.1109/ICICICT1.2017.8342670