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 TWTA. 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 $\alpha_s$ 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 ($\alpha_s$) 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].

$$\ln\left(\frac{t_2}{t_1}\right) = \frac{E_a}{k} \cdot \left(\frac{1}{T_2} - \frac{1}{T_1}\right)$$

(1)

Where:

$t_1$ = reference time to failure at reference temperature $T_1$
$t_2$ = time to failure at temperature $T_2$
$E_a$ = Activation energy (unique to process)
$T_1$ = Reference temperature (Kelvin) for failure time $t_1$,
$T_2$ = Temperature (Kelvin) to calculate failure time $t_2$
Equation (1) calculates median time \((t_2)\) of failure based upon a known median time \((t_1)\) of failure, failure activation energy \((E_a)\) and failure temperature \((T_1)\). 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)\(P_{\text{out}}\) : 100 Watts
- Bandwidth : 240-260 MHz
- Power added efficiency \((\eta)\) : 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.

\[ T_{ch} = R_{th} \times P_{dissipation} + T_a \quad (2) \]

Where:
- \( T_{ch} \) = Device (FET) Channel temperature
- \( T_a \) = Base plate temperature (ambient temperature)
- \( P_{dissipation} \) = Total power dissipation as heat
- \( R_{th} \) = 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](image)

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](image)

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.

<table>
<thead>
<tr>
<th>Device Configuration</th>
<th>Pout (watt)</th>
<th>PDC (watt)</th>
<th>Pdissipation (watt)</th>
<th>Device η (%)</th>
<th>Effective $R_t/h$ (°C/Watt)</th>
<th>$T_{ch}$ (°C) @ 60 °C base plate</th>
<th>$T_{ch}$ (°C) @ 40 °C base plate</th>
<th>SSPA η (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single Device</td>
<td>100</td>
<td>170</td>
<td>70</td>
<td>60</td>
<td>1.0</td>
<td>130</td>
<td>110</td>
<td>45</td>
</tr>
<tr>
<td>Each device of Push-pull Configuration</td>
<td>55</td>
<td>105</td>
<td>(Total 210)</td>
<td>55</td>
<td>1.0</td>
<td>110</td>
<td></td>
<td>37</td>
</tr>
</tbody>
</table>

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.
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 into 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.

![Proposed Balanced Configuration for RF MOSFET](image)

**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 30:1 means 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 of 0.3 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.

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>RF output power (nominal) Pout</td>
<td>150 Watts</td>
</tr>
<tr>
<td>Bandwidth</td>
<td>1110-1130 MHz</td>
</tr>
<tr>
<td>Power added efficiency (η)</td>
<td>55 %</td>
</tr>
<tr>
<td>Thermal Resistance of device</td>
<td>0.7˚C/W</td>
</tr>
</tbody>
</table>
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.

<table>
<thead>
<tr>
<th>Device Configuration</th>
<th>Pout (watt)</th>
<th>PDC (watt)</th>
<th>Pdissipation (watt)</th>
<th>Device η (%)</th>
<th>Effective Rth (˚C/Watt)</th>
<th>Tch (˚C) @60 °C base plate</th>
<th>Tch (˚C) @40 °C base plate</th>
<th>SSPA η (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single Device</td>
<td>150</td>
<td>272</td>
<td>122</td>
<td>55</td>
<td>1.0</td>
<td>182</td>
<td>162</td>
<td>45</td>
</tr>
<tr>
<td>Each device of Push-pull Configuration</td>
<td>90</td>
<td>180</td>
<td>90</td>
<td>50</td>
<td>1.0</td>
<td>150</td>
<td></td>
<td>38</td>
</tr>
</tbody>
</table>

After 8 years when the base plate reaches above 40 °C
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 large 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](image)

A voltage divider network is used to generate reference voltage $V_{\text{ref}}$ 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]. $V_s$ is the constant voltage coming from the regulator and $R_{\text{th}}$ 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 $V_{\text{ref}}$ can be obtained from the network as per equation below:

$$V_{\text{ref}} = V_s \left[ \frac{R_3 + R_{\text{TH}}}{R_2} \right] \left[ \frac{R_1 + (R_3 + R_{\text{TH}})}{R_2} \right]$$

(3)

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

$$V_{\text{ref}} = V_s \left[ \frac{R_2}{(R_1 + R_2)} \right] R_{\text{TH}} + \left[ \frac{R_3}{R_1 + R_2} \right] \left[ R_{\text{TH}} + \left( \frac{R_1 R_2 + R_2 R_3 + R_1 R_3}{R_1 + R_2} \right) \right]$$

(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. $R_1$, $R_2$ & $R_3$, the required reference voltage can be obtained. A simple calculator can be programmed in MS-Excel or MATLAB and by varying $R_1$, $R_2$ & $R_3$, 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:

