Development of a naturally aspirated thermosyphon for power amplifier cooling

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Abstract. This paper details the early development steps of a two-phase thermosyphon thermal management solution for power amplifiers (PA) in the telecommunication industry. These components, attached to a vertical PCB within an enclosure between the RF filter and a natural or forced convection heat sink, dissipate a large amount of heat with a high heat flux density. Currently cooled by direct contact to a shared heat sink, they tend to spread heat towards other components of their board, affecting their reliability. A thermosyphon thus appear as an ideal thermal management solution to transport the heat from the power amplifiers in order to dissipate it to a remote and dedicated natural convection heat sink. In the present study, the performance and the heat spreading of a forced convection unit is measured. A thermosyphon solution is then designed with a flat vertical evaporator and a radial natural convection heat sink and condenser. The performance of the thermosyphon thermal management solution is measured and compared to the initial solution. The limits and improvement needs of the thermosyphon solution are then discussed.

1. Introduction

The reliability and failure of electronic components is highly related to the temperature levels and variations to which they are subject [1]. Appropriate thermal management solution is thus a key design feature for enhancing their reliability. However, although each component has different temperature sensibility characteristics, different components often share the same thermal management solution on the same PCB.

This is the case for telecom equipment such as Remote Radio Head (RRH). This equipment is composed of several parts including the radio-frequency (RF) filter and the main PCB comprising a large number of electronic components. This PCB is often enclosed between the RF filter or a radio shield, and a large heat sink acting as thermal management for the electronic components. The heat sink usually dissipates heat to ambient air by natural convection on outdoor units and by forced convection on indoor units. Among the different electronic components that need to be maintained at adequate temperature, the power amplifiers (PA) dissipate high heat fluxes, up to 140 W. As they share the heat sink with all other components, they tend to thermally pollute them through the heat sink and compromise their reliability.
In order to improve the reliability of both the power amplifiers and the other electronic components, a thermosyphon solution is considered in order to transport the heat flux produced by the PA to a remote, dedicated heat sink. The objective of this solution is not only to enhance the thermal management of the PA, but also to decouple thermally the PA from the other components of the same board, unlike other solutions such as vapor chamber heat sinks [2].

Thermosyphons are recognized as an attractive thermal management solution in many applications due to their passive operation, low cost, and ability to transfer heat over relatively large distances with small temperature differences. Unlike heat pipes, thermosyphons operate under the influence of gravity and without the use of a wick to return the condensate to the evaporator. For this reason thermosyphons are orientation specific and most commonly they consist of straight tubes placed vertically to ensure the liquid fully returns to the evaporator.

2. Experimental Apparatus

The first step of the development of a thermosyphon thermal management solution for RRH consists in a proof of concept in situ of a thermosyphon prototype, and of the estimation of the performance in terms of thermal resistance and thermal spreading of both the original and the modified version. This section describes the indoor forced-convection Transmit Receive Duplex Unit (TRDU) chosen and the design of the thermosyphon prototype.

2.1. Test telecommunication equipment

The indoor unit on which the prototype thermosyphon is tested consists of a different parts stacked, as depicted in Figure 1. The main part of interest is the PA board. It is on one side protected by a radio shield and placed against the radio filter. On the other side, the board is in direct contact with an aluminium casted finned heat sink. Another PCB is located 3 mm apart of the heat sink. The whole system is enclosed into a rack structure. A fan array at the bottom ensures the air flow and subsequent forced convection on the heat sink.

The PA board comprises many electronic components. The main heat dissipating components are the power amplifiers, which are grouped into 3 pairs (Figure 2). Each pair consists of a main and a peak power amplifier. In normal operation, most of the power, and thus most of the heat generation concerns the main PA. The objective of the current development is to provide an adequate thermal management of the PA without polluting thermally other components of the same PCB which may be
more temperature sensitive. The PA board of the test apparatus has been modified in order to directly control the power consumed and the subsequent heat flux generated by the power amplifiers.

![Figure 2: Location of the PA on the board](image)

2.2. Thermosyphon prototype

A thermosyphon is a closed system containing a fluid (see Figure 3). It comprises an evaporator in contact to the heat source, an adiabatic section for thermal transport and a condenser which releases the heat transported. In the developed solution, the evaporator is a rectangular copper container. Each pair of power amplifier shares a same evaporator, to which they are in contact using a thermal interface material (TIM). The heat is conducted through the copper wall of the evaporator and transferred to the working fluid, which is water. The water thus boils and the heat is transformed into latent heat in the vapour phase.

![Figure 3: Schematic of the thermosyphon](image)

The vapour is transported through the adiabatic section, which consists in a 10 mm inside diameter, 50 cm long stainless steel pipe. The vapour then enters the condenser, which is in direct contact to a
natural convection heat sink. The latent heat is released to heat sink by condensation. The heat is then conducted through the heat sink and released to the ambient air by natural convection. The condensate formed into the condenser flows back to the evaporator due to gravity.

Both advantages of a thermosyphon solution are illustrated in Figure 4. First, the evaporating and condensing temperature are close to each other, at the saturation temperature of the fluid, which allows dissipating efficiently the heat flux to the air with a hot heat sink. Also, the adiabatic transport of the latent heat in the pipe gives the opportunity to separate the heat sink at a remote location from the heat source.

![Figure 4: Thermosyphon in operation, normal and infrared visualisation](image)

For the tests using the thermosyphon prototype, the test facility described in Section 2.1. is modified by cutting a hole through the heat sink, the radio board and the case in order to bolt the thermosyphon evaporator at the back of the central PA pair.

3. Thermal characterization

In order to properly characterize the performance of the thermosyphon solution, a methodology is developed with its adequate metrology in order to define the cooling efficiency and the thermal spreading on the board. The performance is measured for both the initial forced convection thermal management solution and with the use of the thermosyphon prototype. The two solutions are then compared, and conclusions are discussed in order to define the improvements needed for the next steps of development.

During the tests, only the main power amplifier of the central PA pair is powered, in order to best estimate the heat dissipation in the board. As the components are cooled by the back of the board (either by the forced convection heat sink or by the thermosyphon), the board temperature is measured by means of IR visualization on the front of the board (see Figure 5). A black paint of homogeneous and known emissivity is applied at four key locations on the board in order to measure accurately the local temperature (see Figure 6). In addition, the ambient air temperature is measured by a thermocouple.
The temperature measurements are summarized in Table 1. The total thermal resistance $R_{th}$, or cooling efficiency, is defined in [K/W] as a function of the temperature difference between the main PA and the ambient air and of the heat flux $P$ dissipated by the transistor, such as:

$$R_{th} = \frac{T_{\text{main}} - T_{\text{amb}}}{P}$$

**Table 1: Description of the temperature measurements**

| Label    | Description                                                                 |
|----------|-----------------------------------------------------------------------------|
| $T_{\text{main}}$ | Temperature on the main power amplifier component                           |
| $T_{\text{peak}}$ | Temperature on the peak power amplifier component                           |
| $T_{5\text{cm}}$ | Temperature at a central location about 5 cm up from the PA pair (downstream) |
| $T_{\text{driver}}$ | Temperature close to the driver chip, thermally sensitive component, about 10 cm downstream from the main PA |
| $T_{\text{amb}}$ | Ambiant temperature, entering either the forced convection heat sink or the natural convection dedicated heat sink of the thermosyphon |

The heat spreading $S_i$ is defined in [%] at each location $i$ on the board such as:

$$S_i = 100 \times \frac{T_i - T_{\text{amb}}}{T_{\text{main}} - T_{\text{amb}}}$$

**4. Results and Discussion**

Table 2 presents three sets of results, with a power of 100 W dissipated in the main power amplifier. The first set was measured with the original forced convection thermal management solution. The second set was measured with the thermosyphon installed as a cooling solution for the
central PA pair, keeping forced convection on the remaining area of the heat sink to cool the rest of the PA board. For the third set, forced convection was avoided on the heat sink by turning off the fans. Table 3 presents similar sets of results for a power of 140 W provided to the main PA.

Table 2: Heat load of 100 W on the main PA

| Total thermal resistance | Spreading Peak | Spreading 5cm | Spreading driver |
|--------------------------|----------------|--------------|-----------------|
| K/W                      | %              | %            | %               |
| Forced convection        | 1.12           | 18.1         | 25.5            | 13.8            |
| TS and fan on            | 0.94           | 39.8         | 15.3            | 6.7             |
| TS and fan off           | 1.02           | 50           | 27              | 16.5            |

The cooling efficiency has been improved using the thermosyphon prototype by decreasing by up to 25 % the total thermal resistance between the main PA and the ambient air. The efficiency increases for both the forced convection and the thermosyphon solutions when increasing the power dissipated, due to enhanced convection on higher temperature heat sinks. When the fan is on, the forced flow contributes to cooling the thermosyphon evaporator, improving its cooling efficiency.

As both main and peak power amplifiers share the same evaporator in the thermosyphon solution, they are thermally linked. Consequently, the thermal spreading between the PA is greatly enhanced. Concerning the heat spreading to other locations on the board, it is significantly decreased using the thermosyphon with the fan on, as the PA are thermally decoupled from the board. However, there is no improvement with the fan off as the stagnant air in the fins of the board heat sink is slowly heated by the thermosyphon evaporator.

Table 3: Heat load of 140 W on the main PA

| Total thermal resistance | Spreading Peak | Spreading 5cm | Spreading driver |
|--------------------------|----------------|--------------|-----------------|
| K/W                      | %              | %            | %               |
| Forced convection        | 1.05           | 19           | 27.5            | 15.5            |
| TS and fan on            | 0.79           | 40.1         | 14.7            | 5.2             |
| TS and fan off           | 0.94           | 49.4         | 27.6            | 17.6            |

5. Conclusions
A thermosyphon prototype equipped with a dedicated natural convection heat sink has been successfully tested as a thermal management solution for power amplifiers on an existing RRH unit. The design of this first prototype was sufficient to slightly improve the cooling efficiency of the PA, while reducing heat spreading from the PA towards other components sharing the same PCB.

References
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