25/25
- Excellent report with detailed analysis of the resistance network. Well-written and organized.
- Interesting cooling approach employed.
- To ensure that the increase in the power limit is due to the new components, you can drop the new components and check if the power limit drops back down.

Thermal Management Strategies for Next-Generation Smartwatches

Saeel Shrivallabh Pai
School of Mechanical Engineering
Purdue University
West-Lafayette, USA
pai15@purdue.edu

***Abstract*— As part of the ME511 final project, a new design for next-generation smartwatches has been proposed and its performance has been analyzed. Using a steady state analysis, it has been shown that the proposed design has better thermal management capabilities than the existing devices. As compared to the peak power of 0.5W in the state-of-the-art smartwatches available today, the proposed design is able to sustain a continuous steady state operation at peak powers of about 1.65W, which is more than three times the maximum power in present devices. The concept of using additional components of the watch to dissipate the heat generated in the device has been shown to have great promise and should be explored further.**

Keywords—thermal management, passive cooling, wearables, smartwatches

I. Motivation and Introduction

The use of wearable devices has grown tremendously over the past few years. In 2018, the shipment of wearable devices was 178.91 million, and is expected to reach 453.19 million in 2022. More than half of all the wearable devices are the wrist worn devices (e.g., smart watches, smart bands, smart bracelets, and fitness trackers) and as of 2019, one in five Americans use a wrist worn device [1,2].

Wrist worn devices have been used in many applications ranging from medicine and healthcare, to sports, education, human-computer interaction, and security, through use of many sensors located on the device itself. These sensors monitor several health parameters such as body movement, temperature, heart rate, etc. People have been using smartphones for a long time now, and hence, expect the smartwatches to provide all these monitoring services as additional services over and above the functionalities of a smartphone. However, this desired increase in functionality comes with increase in processer heat dissipation. In a device such a smartwatch, the size, surface area and its application make the use of active cooling techniques difficult. Therefore, passive cooling techniques are our most viable options. Because of all these constraints, most of the available smartwatches have a power dissipation of <200mW (the recently released Samsung Galaxy Watch 3 has gone up to around 500mW), as compared to a power dissipation of 0.5-3W in a smartphone[1].

In this project, we propose to design a passive thermal management solution for a smartwatch with a peak power dissipation of at least 1W (if not more).

A. Nomenclature

T_j	junction temperature, K
h	convective heat transfer coefficient, W/m^{2}K
k	thermal conductivity, W/mK
$\dot{Q}$	heat transfer rate, W
A_s	footprint area of heat source, m^2
A_p	footprint area of heat sink base plate, m^2
R_{cond}	conductive thermal resistance
R_{conv}	convective thermal resistance
R_S	spreading thermal resistance

B. Abbreviations

BLT	bond line thickness
CPU	central processing unit
GPU	graphics processing unit
PCB	printed circuit board
PCM	phase change material
PGS	pyrolytic graphite sheet
TDP	thermal design power
TIM	thermal interface material

II. Problem Description

A. Operating Conditions

An Android smartwatch, like the Samsung Galaxy Watch 3, which is the state-of-the-art smartwatch by Samsung, typically operates in 4 different states which have diverse power characteristics: the awake state, the dozing state (dimmed watch face display and reduced system activity), the sleep state (screen further turned off) and the charging state. The study by Lie et al. [3] finds that the smartwatch's awake state accounts for only 2% of the usage time but consumes (and dissipates) around 27% of the total energy. Each awake state lasts for a very short time of about 13 seconds but are very frequent (around 72 times a day). In contrast the sleep state accounts for around 25% of the time and dissipates 17% of the total energy. Table 1 gives the time and energy splits and the power of energy consumption in a smartwatch during a 24hr cycle. For our calculations, since there is no significant useful work done, we consider that all the energy drawn in by the device is converted into heat.

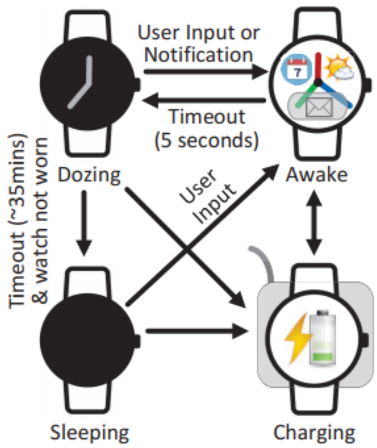


Fig. 1. Device states for an Android watch [3]

State	Awake	Dozing	Sleeping	Charging
Duration	2.0%	50.6%	24.7%	22.8%
Energy	27.2%	56.0%	16.8%	N/A
Power (for the proposed design)	1W (more than twice the current peak power)	40mW	15mW	N/A

Table 1. Duration, energy and power consumption by an Android watch in its different operative states [3]

From table 1, we see that for the purpose of thermal modelling, the power states of the smartwatch can be divided into 2 main categories: 1) the low power continuous operation (dozing and sleeping), and 2) the high power burst (awake). The thermal management solution that we propose will address both these power states. To make the smartwatch a next-generation device, we will work under the assumption that the peak power which we will be operating under will be at least twice that of the maximum peak power of the best watches available today. Since we are designing a passively cooled solution, a design that is able to tolerate a higher processor power will easily be able to function effectively in lower power conditions as well without any operational changes from the user side, and we will explicitly show that. Moreover, we will evaluate the performance of our solution in two different ambient conditions, one at 25°C and one at 40°C.

B. *Boundary Conditions*

The device that we have looked while determining the power boundary conditions is the Samsung Galaxy Watch 3 which was released in Aug 2020. This watch uses a 1.15GHz processer, the Exynos 9110 Mobile Processer, which uses an ARM Cortex A53 (1150 MHz and Dual Core) as the processer and a Mali-T720MPI GPU. The Exynos 9110 is built on a 10nm process technology, and has a SoC-ePoP package type, with an area of 8 x 9.5mm^2. We took shall be considering a similar chip area in our design [4,5].

The Cortex A53 processer is generally used in several smartphones and is an extremely powerful processer for a smartwatch. The power dissipation chart of the Cortex A53 chip is shown in Fig. 2. For dual-core processer operating at a maximum frequency of 1150Hz, we can see that the maximum power dissipated is around 380mW. With some additional power dissipated by the GPU (lower power, but exact value not available), the total power dissipated by the Exynos 9110 Mobile Processer is still less than 500mW.

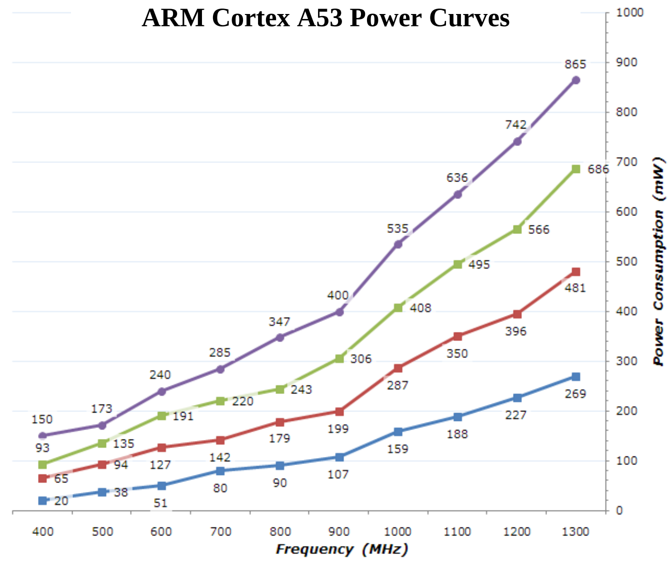


Fig. 2. Power curves for the ARM Cortex A53 processer chip [6]

In this project, we propose to design a thermal management solution for next-generation smartwatches dissipating a peak power of at least 1000mW, which is more than twice the peak power dissipation in the latest design currently available.

The thermal management solution that we design should be able to effectively dissipate the high-power fluxes (high for passive cooling) while maintaining temperatures of all the critical points below the specified limits. From the chip manufactures, we have a limit on the maximum allowable chip temperature for safe operation. For the Exynos 9110, this maximum allowable chip temperature is 70°C. For the safe operation of the battery pack inside the smartwatch, the temperature at any point on the battery pack should stay below 60°C. For a smartwatch, however, these 2 temperature limits aren't the defining boundary conditions. The main defining boundary condition for a smartwatch is the temperature of those parts of the watch that come in contact with human skin, i.e. the temperatures of the back of the watch casing, and the temperatures of the inner side of the watch strap. Studies have shown that low-temperature burns may be caused if a device operating a temperature of more than 48°C stays in contact with the skin for more than 10mins or a temperature of 43°C for 8 hours or longer [1]. These, however, are temperature limits to avoid any injury to the body. The temperature limit for comfort, however, are lower. In our design, we will try to limit the maximum peak temperature of the back of the watch case and the inner side of the watch strap to less than 38°C. All the design calculations will be done assuming a hand-watch system with a

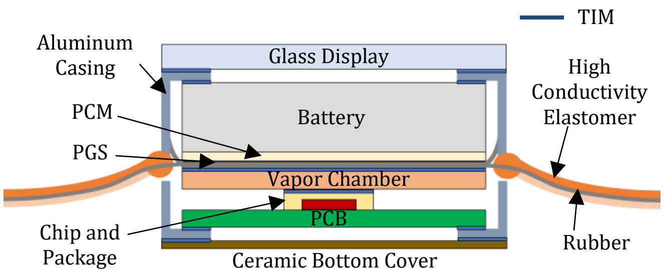


Fig. 3. Schematic of a cross section of the proposed smartwatch design

human skin temperature of 33℃ and an ambient temperature of 25℃.

For our design, we have chosen a watch of dimensions 40x40x11mm, with a belt width of 22mm and thickness of 3mm.

C. Proposed Cooling Technique for a Next-Gen Design

We propose a passive cooling solution (since active is not really an option), and in order to manage the high power burst and its continued operation during the awake state, as well as to manage the low power heat dissipation during the other states, we propose the following 3 features in our design.

1. **Watch belts as heat exchange surfaces** to increase the area from which natural convection takes place, cause in devices which rely on natural convection, the outer casing to ambient resistance is the major bottleneck.
2. **Vapor chambers** for heat spreading inside the device.
3. **PCM** inside the watch body to deal with the sudden burst of power during the frequent but short-lived awake state.

III. Design and Analysis

A. Proposed Overall Design

In the proposed design, the overall layout of the smartwatch has been kept like the layout of watches available today. The bottom cover of the watch is made from a ceramic, which has a couple of sensors embedded in them. Right above the bottom cover is the PCB on which lies the chip. The vapor chamber has been located right above the chip package and has been fixed to it by means of a TIM. Above the vapor chamber is a layer of PGS, from which emerge 2 sets of PGS wings. One set (opposite ones) goes into the belts of the watch, while the other set is connected to the casing of the watch to conduct heat to the outer casing. Above the PGS sheet is where the PCM-composite has been placed. The PCM is selected so that the melting point is around 44℃ and the metal-insert composite structure has been designed to have an effective solid thermal conductivity of around 6.7K/W. Further details on this design will be discussed a little later. The battery pack is located above the PCM-composite and is connected to the aluminum casing by means of cantilevered projections in the aluminum casing, and above that is the glass display. The PGS that extended inside the belts of the watch conduct some heat from the interior of the watch to the belts from which it can be dissipated to the ambient and to the user's hand. The top face of the belt is made up of a high conducting elastomer and has fins engraved on it to further increase its surface area for enhanced heat transfer, while the face of the belt in contact with the skin is made of an insulting rubber to discourage the heat from flowing into the hand of the user. A schematic of the proposed design is shown in Fig. 3, and the thermophysical properties of the components and material are presented in Table 2. The *a* and *b* values, which are the thicknesses of the vapor chamber and the PCM-composite will be decided based on some other considerations which will be discussed subsequently.

Table 2

Component	Properties
Bottom Cover	Material: Ceramic k = 3W/mK [7] Dimensions: 40×40×0.5 mm^3
PCB	k = 13W/mK [8] Dimensions: 35×35×1 mm^3
Package	Dimensions: 10×10×0.75 mm^3
Vapor Chamber	k = 4000W/mK [9] Dimensions: 35×35×a mm^3
PGS	k = 2000W/mK [10] Thickness: 25μm Extension to Al Case: 0.5 cm each Extension into belt: 7.5 cm each
TIM	BLT: 0.1mm k = 3W/mK [11]
PCM-Composite [12,13]	With Embedded Crossed Plate Fin Porosity: 86% PCM: 22 Carbon Paraffin Wax Melting Point = 44℃ $\rho_{paraffin}$=900g/m^3 $H_{sf,paraffin}$=249kJ/kg k = 6.7W/mK Dimensions: 35×35×b mm^3
Battery Pack	k = 10W/mK [8] Dimensions: 35×35×4 mm^3
Display	Material: Glass k = 0.8W/mK [14] Dimensions: 40×40×1.5 mm^3
Casing	Material: Aluminum k = 236W/mK [8] Thickness: 0.5mm
Belts	Material 1: Celanese Coolpoly D8102 k = 2.3W/mK [15] Material 2: Rubber k = 0.15W/mK [16] Dimensions: 22×75×3 mm^3 each
Skin layer	k = 0.4W/mK [8] thickness: 3mm

B. Equations

The equations used in this work are discussed in this section. The conduction and convection resistances are calculated using the following formulae:

$$R_{cond} = \frac{t}{kA_c},\ R_{conv} = \frac{1}{hA_{surf}}, \tag{1,2}$$

Where t is the material thickness in the direction of heat conduction, A_c is the area of the cross section perpendicular to the direction of heat transfer, and A_{surf} is the surface area for convective heat transfer. The spreading resistance is calculated from

$$R_s = \left(\frac{\sqrt{A_p}-\sqrt{A_s}}{k\sqrt{\pi A_p s}}\right)\frac{\frac{\beta k}{h_{eff}}+\tanh(\beta d)}{1+\frac{\beta k}{h_{eff}}\tanh(\beta d)} \tag{3}$$

$$\text{Where } \beta = \frac{\pi^{1.5}}{\sqrt{A_p}} - \frac{1}{\sqrt{A_s}},\ h_{eff} = \frac{1}{R_{eff}A_p} \tag{4,5}$$

And A_s and A_P are the areas of the source and spreading surfaces respectively and R_{eff} is the resistance between the sink side face of the spreading surface and the ambient. The constriction resistance is calculated from

$$R_c = \frac{F}{4k_m a}\ \text{, where } F \approx \left(1-\frac{a}{b}\right)^{1.5} \tag{6}$$

This formula has been derived for the case of heat transfer between two heat flux tubes of radii *a* and *b* (*b≥a),* and k_m is the harmonic mean conductivity, defined as

$$k_m = \frac{2k_1k_2}{k_1+k_2} \tag{7}$$

The area normalized resistance of the TIM is found using the following formula

$$R_{TIM} = \frac{BLT}{k_{TIM}} + R_{1-2} \tag{8}$$

where R_{1-2} is the sum of the contact resistances between the TIM and the top and bottom layers. The area-normalized resistance of PCM is also modelled along similar lines as

$$R_{PCM} = \frac{L}{k_{se}A} + R_{1-2} \tag{9}$$

To simplify the analysis, the value of R_{1-2} has been assumed to be $5 \times 10^{-5}\text{Km}^2/\text{W}$, which is a nominal value for many TIM-Cu interfaces according to [11]. This value has of R_{1-2} has been used for all the TIM-material and PCM-material interfaces for simplicity.

C. Assumptions For Analysis

The thermal analysis has been carried out by considering the smartwatch, the ambient and the user's hand as a whole system. Thus, the ambient and the user's forearm act as heat sinks to the smartwatch. In the analysis of the design, it has been assumed that the watch is operating in a steady state condition. In reality, this isn't the case, but the steady state analysis will give us something to start with. A heat flow between different components of the watch and the ambient and user's skin is modelled as a thermal resistance network, which is explained in more detail in the next subsection.

An important assumption that we have made to model the heat flow in the smartwatch is that the entire aluminum casing of the watch is at the same temperature and that there is no thermal gradient in the aluminum casing. Another assumption that we have made is that the heat flux at the package face is uniform and there are no hotspots on the package of the chip. In some places, we have calculated the thermal spreading resistances using the equations meant for cylindrical geometries even though our geometries were not compliant. We have also assumed that there is perfect contact between the watch belt and the user's skin and there is no air gap in between.

For the PCM-composite, we choose a PCM embedded with aluminum crossed plate fins in a matrix of docosane (22 carbon alkane). Srivatsa et al [12] obtained an effective solid conductivity of 6.7W/mK with an eicosane (20 carbon alkane) matrix embedded with crossed fin aluminum fins and a porosity of 86%. From the analysis in [12], we see that in the solid state, the effective thermal conductivity of the composite in a solid state is a much greater function of the metal fins than of the paraffin. Hence, for our application, we too consider a PCM-composite material with embedded aluminum crossed fins and a porosity of 86% and assume an effective thermal conductivity of 6.7W/mK. Docosane has a latent heat of melting of 249kJ/kg [13]. If the PCM were to absorb a power of 1.5W for 2 minutes, the weight of docosane needed would be 0.72g, which implies a volume of 803mm^3. Thus, a PCM-composite of thickness 0.75mm would be needed.

D. Thermal Resistance Network

The heat in the smartwatch is generated by the CPU of the watch located inside the chip package. Some of the heat generated goes up the vapor chamber and to the PGS. Once the heat reaches the PGS, it has several more flow paths to take. Some of the heat is conducted to the aluminum casing through the PGS connection to the casing. Some of the heat goes up the PCM-composite and battery and again to the aluminum casing. The rest of the heat from the PGS layer gets conducted to the belts of the watch via the embedded PGS inside of it. From the belts, some of the heat gets conducted to the user's skin while the rest of the heat is lost to the ambient. While some of the heat at heat generated by the device chip takes the flow path described above, the rest of the heat from the deice chip goes down the PCB and the ceramic bottom cover to the aluminum casing. All the heat transferred to the aluminum casing is ultimately lost to the ambient via the process of natural convection, while all the heat that flow down the bottom cover of the watch is transferred to the skin of the user. At steady state,

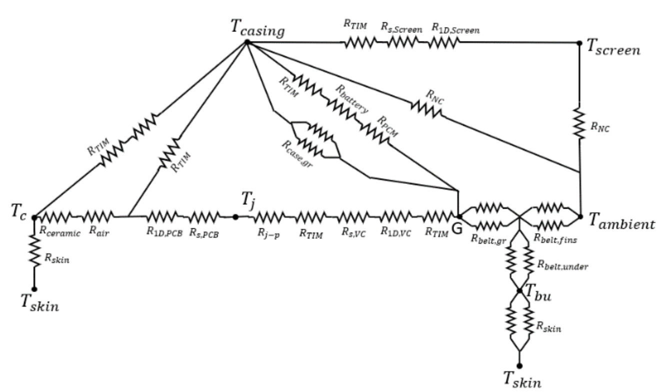


Fig. 4. Thermal resistance network for the proposed design of the next-generation smart watch

if these heat flow pathways are modelled as thermal resistances, we get the thermal resistance network shown in Fig. 4.

E. Calculation and Optimization of Resistances

All the resistances shown in the thermal resistance network in Fig. 4 can be calculated from known formulae or approximations of known formulae using thermophysical material properties and physical dimensions of the component.

The belt is taken to be 3mm thick, with the PGS at a depth of 2mm from the surface facing the ambient. If the depth of the engraved rectangular fins on the face of the belt facing the ambient is 2mm (i.e. fin is 2mm long), then from the formula for optimal fin dimensions $t = 0.9929\frac{hL^2}{k}$, we get the optimal fin thickness to be 7µm, which is clearly not feasible. Thus, from a practical standpoint, we have chosen the fins to be 1mm wide and have an inter fin gap of 1mm, and the length of each belt is taken to be 7.5 cm. Approximating the wrist as a cylinder of 5cm diameter and the temperature of the belt as a nominal 33℃, from [17], an online natural convection coefficient calculator, we get h =4W/m^{2}K. From the dimensions and coefficient of convective heat transfer, and a convective fin tip condition, we get a surface to ambient thermal resistance of 50.8K/W for the fin array on each belt. The face of the belt that comes in contact with the skin is made up of a rubber of thickness 1mm, and this gives a thermal resistance of 4K/W per belt.

The TIM between the chip package and the vapor chamber gives a thermal resistance of 0.8333K/W. To keep the total thickness of the smartwatch less than or equal to 11mm, it is required that the thickness of the PCM-composite plus the thickness of the vapor chamber should be 1.75mm. Since the PCM-composite has a thickness of 0.75mm, the maximum thickness of the vapor chamber can be 1mm. The total resistance of the vapor chamber is the 1D conduction resistance plus the spreading resistance between the TIM on top of the chip package to the vapor chamber. From Fig. 5, the total resistance offered by the vapor chamber is minimum at a thickness of 1mm, which is the maximum allowable thickness due to the size constraint. At this thickness, the total thermal resistance offered by the vapor chamber is 0.04K/W.

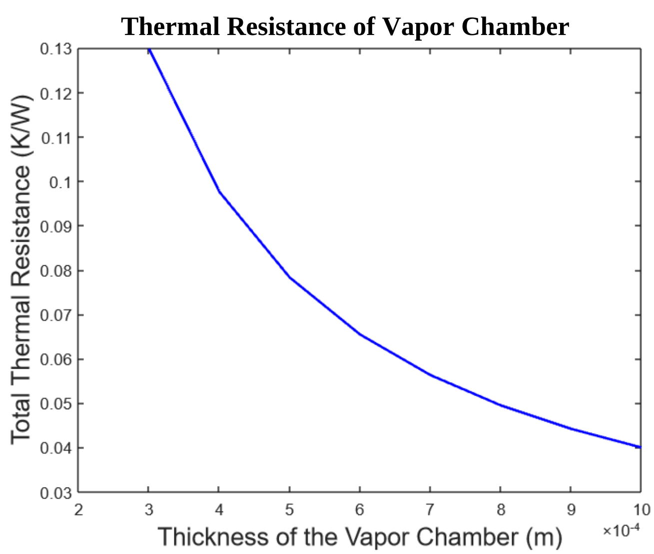


Fig. 5. Total thermal resistance of the vapor chamber as a function of its thickness

Since the thickness of the PGS is very small (25µm), the through plane thermal resistance of 0.001K/W is neglected and only the in-plane thermal resistance is considered. Although the PGS extends throughout the belts, the distance for the purpose of thermal resistance calculation is considered as the distance from the center of the watch to the middle of the belts. This distance is 2+7.5/2 = 5.75cm, and consequently, the in-plane thermal resistance of the PGS from the watch interior to the belts is 26.14K/W per belt. Similarly, the PGS extensions which connect to the aluminum watch casing are 0.5cm long, and the center to center distance is 2.25cm. Thus, the in-plane thermal resistance associated with these extensions is 6.42K/W per extension. The TIM connecting the PGS extensions to the casing contribute an additional 0.47K/W per connection. Therefore, the resistance between the center of the PGS to the aluminum casing is 6.9K/W per extension, and the TIM connecting the PGS to the vapor chamber contributes a thermal resistance of 0.068K/W.

The 1D resistance plus contact resistances for the PCM-composite comes to 0.1321K/W for a PCM-composite 0.75mm thick. The 1D thermal resistance offered by the battery pack is 0.3265K/W. If the aluminum ledges are designed to extend 2mm inside the footprint of the battery on all sides, then the contact area between the battery and the aluminum casing is 0.035^2-0.031^2 = 264mm^2. Therefore, the TIM resistance plus the constriction resistance turns out to be 0.3155K/W and 0.557K/W respectively. On the other hand, the resistance offered by the air gap between the battery pack and the display is 19.27K/W. For simplicity of calculation, the heat transfer from the battery pack to the display is neglected. In reality, the downstream resistances, that between the display and the ambient and that between the casing and the ambient should also be taken into consideration before deciding to neglect the heat transfer between the battery and the display, but as we shall see later, the resistance between the display and the ambient turns out to be larger than the resistance between the casing and the ambient. Thus, this turns out to be a decently good approximation. Also, for calculating the constriction resistance, we have used the formula derived for circular tubes even though this geometry is way different. Thus, we calculate the thermal resistance between the PGS and the casing along the PGS→PCM→ battery→casing path to be 1.3311K/W. The display is attached to the casing with a TIM, so there is heat transfer between the casing and the display glass. The TIM resistance comes out to be 0.1303K/W, the spreading resistance comes out to be 33.83K/W and the 1D conduction resistance of the display glass is 1.17K/W. This amounts to a cumulative resistance of 35.13K/W between the aluminum casing of the watch and the outer surface of the display glass. To calculate the spreading resistance, we used the formula mentioned in the previous section, which is originally meant for circular cross sections, even though this involved casing to display glass geometry is completely different.

It is considered that the watch is worn on the hand and held horizontally so that the display faces upwards. Under this assumption of an upward facing plate at an approximate temperature of 36℃, from [17], we get the h = 8W/m^{2}K, which gives a display to ambient thermal resistance of 78.125K/W. Similarly, for the aluminum watch casing, which are modelled as vertical walls at 37℃ (slightly hotter than the display cause from the resistance network we see that the temperature of the display should be between that of the aluminum casing and the ambient), we get h = 11W/m^{2}K, which gives a casing to ambient thermal resistance of 71K/W.

Exynos 9110 has a System-on-Chip, Package-on-Package (SoC, PoP) architecture and for such a package, the junction-package case thermal resistance can be approximately taken to be 5K/W [18]. Assuming that the package is at a uniform temperature, and that the heat spreads from the package to the PCB, the spreading resistance between the package and the PCB is 12K/W, where as the 1D resistance of the PCB is 0.06K/W. The PCB is connected to the aluminum casing of the watch through a TIM, and this contributes 0.315K.W to the thermal resistance between the PCB and the aluminum casing. Some amount of heat is conducted from the PCB to the bottom cover of the battery across an air gap of 20K/W resistance. In the case of battery to casing, we used a constriction thermal resistance cause we were assuming that the entire heat from the battery goes to the casing, but in this case, we are considering the resistance between the PCB and the bottom cover as well, and hence are not considering the constriction thermal resistance. The ceramic bottom cover of the watch provides a 1D conduction resistance of 0.1K/W, whereas the spreading resistance with the aluminum casing with which it is in contact is 8.3K/W and the resistance offered by the TIM joining the 2 together is 0.2K/W.

The user's skin is modelled as a 3mm deep layer with the inside temperature as 33℃ [8]. Therefore, the conduction resistance offered by the skin below the bottom cover of the watch is 4.68K/w, whereas the resistance of the skin under each of the 2 belts is 4.54K/W.

F. Solution Method

On grouping the resistance which are in series and parallel in Fig. 4, the network is considerably simplified, and this simplified network is shown in Fig. 6. If we consider a thermal

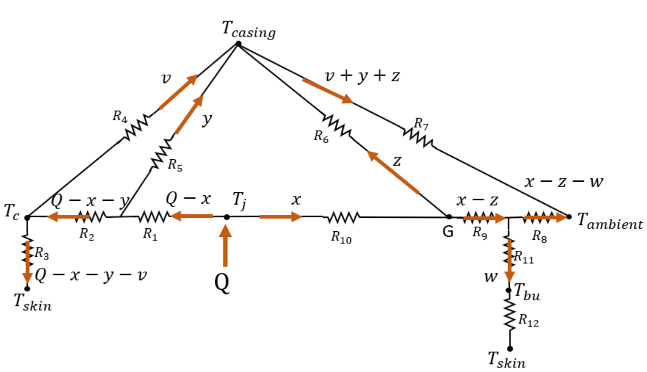


Fig. 6. Simplified thermal resistance network with the heat current distribution in each arm

power Q entering the node T_j and divide it through the different arms of the resistance network using Kirchoff's junction rule, we can then apply Kirchoff's loop rule to write down the 6 equations that we need to solve for our 6 unknowns, T_j, v, w, x, y and z. Once we know the junction temperature T_j and the heat current in each of the arms of the network, we can find the temperature at all points in the system. The system of equations which results from the application of Kirchoff's rules is in the form $\bar{\bar{A}}\vec{X} = \vec{Y}$, where

$$\bar{\bar{A}} = \begin{bmatrix} 1 & R_3 & 0 & R_1+R_2+R_3 & R_2+R_3 & 0 \\ 1 & 0 & R_8 & -(R_8+R_9+R_{10}) & 0 & R_8+R_9 \\ 1 & 0 & -(R_1+R_2) & -(R_9+R_{10}) & 0 & R_9 \\ 0 & 0 & 0 & R_1+R_{10} & -R_5 & R_6 \\ 1 & -R_7 & 0 & -R_{10} & -R_7 & -(R_6+R_7) \\ 0 & -R_4 & 0 & R_2 & R_2+R_5 & 0 \end{bmatrix}$$

$$\vec{X} = \begin{bmatrix} T_j \\ v \\ w \\ x \\ y \\ z \end{bmatrix} \text{ and } \vec{Y} = \begin{bmatrix} T_{skin} + (R_1+R_2+R_3).Q \\ T_{ambient} \\ T_{skin} \\ R_1.Q \\ T_{ambient} \\ R_2.Q \end{bmatrix}$$

This system of equations can be solved by substituting the appropriate values of resistances as per the simplified resistance network, and then inverting the matrix on the left to find out the values of the unknowns. The critical temperatures inside the system are the temperatures of the bottom cover (T_c), underside of the belt (T_{bu}), casing (T_{casing}) and that at the chip junction (T_j). The chip junction temperature is already known by solving the above system of equations, and the rest are found out from

$$T_c = T_{skin} + (Q - x - y - v).R_3 \tag{10}$$

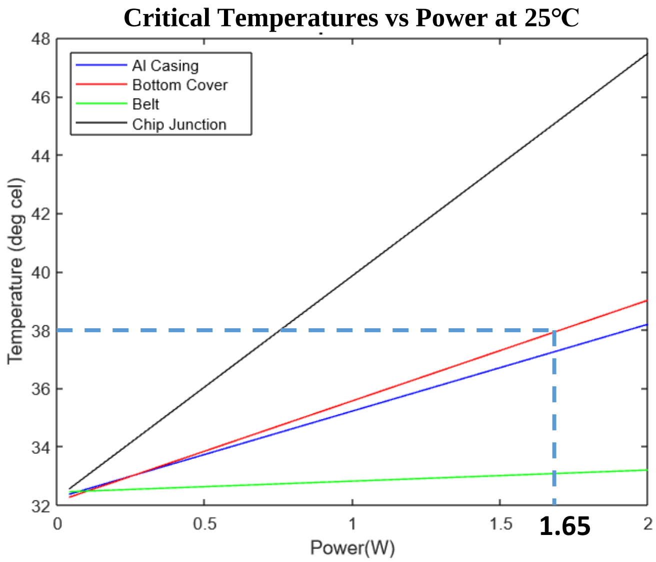
$$T_{casing} = T_{ambient} + (v + y + z).R_7 \tag{11}$$

$$T_{bu} = T_{skin} + w.R_{12} \tag{12}$$

IV. Results and Discussions

A. Evaluation of Maximum Operating Power

As mentioned, we have evaluated the performance of our design of a next generation smartwatch at two different ambient conditions of 25℃ and 40℃ and Fig. 7(a,b) shows the temperature at different points in the system. As seen from both the plots, the chip junction temperature is well below the critical limits, and in both the cases, the temperature of the bottom cover of the watch is the limiting factor. For low power wearable devices like a smartwatch, this is a common occurrence. In an ambient condition of 25℃, our design allows the smartwatch to operate at a maximum steady state power of 1.65W, which is a little more than 3 times the max power of the state-of-the-art smartwatches available today. In an ambient condition of 40℃, this maximum power is 1.2W, which is still more than 2 times the current maximum power. While this is the case at the high power operating point (awake state), at low



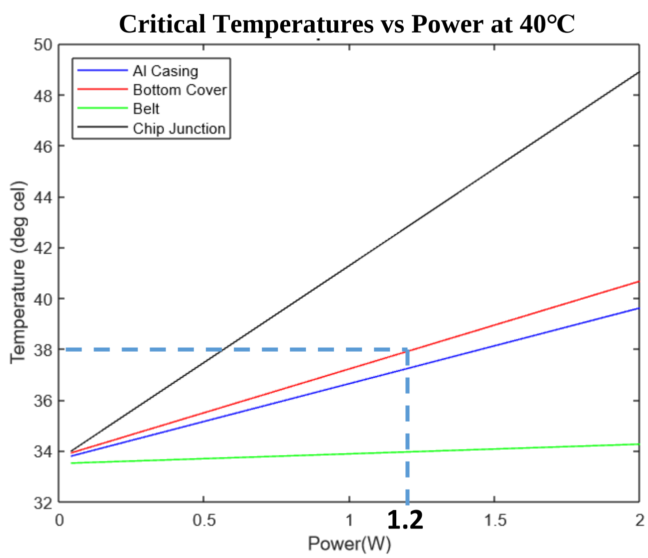


Fig. 7. a (top): Critical temperatures versus maximum power at 25°C, b (bottom): Critical temperatures versus maximum power at 40°C

power operating points of around 40mW (sleeping and dozing) the temperatures at all the points in the smartwatch are at temperatures very close to the skin temperature, and hence is not at all a problem. Unlike in actively cooled devices where a change is flowrate for the two conditions might be requires, a passively cooled device doesn't require any external interference to adjust its performance at different operating conditions and if the device can handle a higher power, then it will have absolutely no issue operating at a lower power.

In both the 25°C and 40°C cases, if we calculate the amount of heat that leaves through the belts (x-z in the above system of equations), we find that this quantity is around 20% of the heat generated by the chip. Thus, we see that using belts to spread the heat is integral to this new smartwatch design.

B. *Thermal Model Verification*

While it is not easy to verify the performance of the proposed model using any simple means, we will argue our way through analytical trends and sanity checks to claim that the design and analysis of the proposed model is sound. The other route which could have been taken to verify the performance of the model was by doing a 3D conjugate heat transfer simulation of the entire watch system. We however eschewed from this route for this project due to the large number of parts in the design and corresponding complications involved.

If we look at the plots in Fig. 7, we see that the temperatures of all the parts of the smartwatch increase with increase in the input power. This is what we would intuitively expect to happen. Moreover, this increase is linear, which is also not surprising since the node temperatures and heat currents in different arms of the network are linear functions of the input heat Q. After solving the system of equations, we find that the maximum chip powers that the smartwatch can operate at are 1.65W and 1.2W for an ambient of 25°C and 40°C respectively. Not only is this range of power consistent with what we would expect from a device that is passively cooled by natural convection, but the maximum operating power at a lower ambient temperature is more that the maximum operating power at a higher ambient temperature. This is what we would intuitively guess. Also, like in most other passively cooled wearable devices, the skin temperature limit is reached before the critical junction temperature is attained. Thus, all these arguments form a good base to claim that the analytical approach taken is trustworthy and that the proposed design is indeed a better design than the existing smartwatch designs, at least as far as the thermal management goes.

C. *Limitations of Modelling Approach and Design*

One of the main limitations of the analytical modelling approach is that the entire analysis is based on a steady state operation of the smartwatch. We know that most of the operation of the watch at higher powers is in a transient regime. However, if the watch is used at a high power for a long enough time so that it reaches a steady state operating point, then our analysis predicts that the maximum power it can operate at will be 1.65W (at 25°C ambient temperature). To take care of the transient nature of operation, we have a phase change material inside the smartwatch with a melting point of 44°C, which will remain a solid under most operating conditions, but which can absorb a power of 1.5W for around 2 mins if the device experiences a sudden power burst, and can then dissipate this heat though the other heat flow channels.

Another drawback of the proposed design is that it might be a little too expensive to be commercially viable. The PGS, vapor chamber, the high conductivity elastomer for the belt and the PCM-composite would all add significantly to the cost of the device.

From an aesthetics perspective, it wouldn't be possible for the user to change the watch belts as and when he/she wants, something that is possible in many smartwatches available today.

V. Conclusion

While the analysis done in the project is mostly at steady state and is not a very rigorous one, it certainly points towards how effective the use of belts as part of the thermal management solution can be. This concept of using belts to increase the heat transfer surface area, and the use of PCMs to absorb the power bursts is certainly worth exploring in the long run. One of the reasons why the high-power mode is so short lived is because the current smartwatch, at less than 500mW of peak power, has very little capabilities. However, at increased peak powers of around 1.5W, the smartwatch will start becoming comparable to a smartphone in terms of capabilities, and this may increase the time for which it is used. In such a scenario, the steady analysis will become more appropriate.

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