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A Comprehensive Study of Efficient Thermal Management Techniques for Handheld Devices

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ABSTRACT

Modern research and development in computer technology has caused the electronics chips to shrink. The increasing needs for hand-held devices that use these VLSI & ULSI chips gave rise to new studies and developments. The increased demand for higher speed processing gave rise to clock speed of the CPU. Recent studies have found out that the failure rate in these chipsets is rising exponentially and is linked with the temperature variations caused by very large scale integration and reduces chip area. It is observed that the devices, currently in the market, heat rapidly. The traditional heat sink and cooling techniques fails to perform with these new devices. The need for a comprehensive study of electronic system design and thermal management in electronics devices is increasing. Study has revealed that miniaturization of the cooling mechanism, and the electronics components should go hand in hand. The study, research and implementation of the new thermal management or cooling techniques for various handheld electronic devices, is the need of the hour. In this paper, the author has explored various methods and effective thermal management schemes for handheld devices.

Keywords : VLSI, ULSI, MP-SoC, CEO, Dynamic Voltage and Frequency Scaling, Thermal Interface Materials

I. INTRODUCTION

The advancement in various fields of science and technology is because of the experimentation and innovation being carried out in the Electrical and Electronics Engineering. The transistor considered as a fundamental building block of processors and microcomputers, is the most important innovation of the 20th century. The increasing demands of the consumer have caused the electronic systems to shrink at a mind boggling rate. The need for more compact designs and advancement in technology has resulted in manufacturing of multiprocessor SoCs which includes CPUs, memories, and communication architectures on a single die. This shrinking of chip size and increased integration has in turn resulted in excessive heat generation. Multiprocessors were introduced recently, which has more than 1 core. Hence, the MP-SoC produces more heat. Due to reduced size of the devices, the heat is not dissipated equally and efficiently. There is a special branch in modern engineering design that works around energy, thermodynamics and heat transfer. This branch is known as Thermal Design.

Gordon Moore, the co-founder of Fairchild Semiconductor and CEO of Intel, stated a law in year 1965. Moore's Law asserts that the number of transistors on a microchip doubles every two years, though the cost of computers is halved [1]. This means that each year, the level of integration, increments noticeably.

In a study conducted by Mingzong Wang on a Chip Scale Package (CSP) they observed that, when the die size is more than 80% of the chip size the rate of heating is increased [2]. Since this package size is shrinking day by day, heat spreading and dissipation is

a challenge. It is reported that the heat flux in the integrated circuits has enhanced from 330 W/cm2 to 520 W/cm2 by the international technology road map for semiconductors [3]. Power dissipation levels in mobile phones are increasing mainly due to gaming, higher power applications, and increased functionality associated with the internet [4]. Heating in handheld devices can be summarized mainly due to two main components: 1) CPU 2) Battery. High temperatures in the chip surroundings may create a number of problems. The transistors can fail to switch properly (this can lead to software or hardware errors). The accelerating clock rates lead to steadily increasing power densities [5].

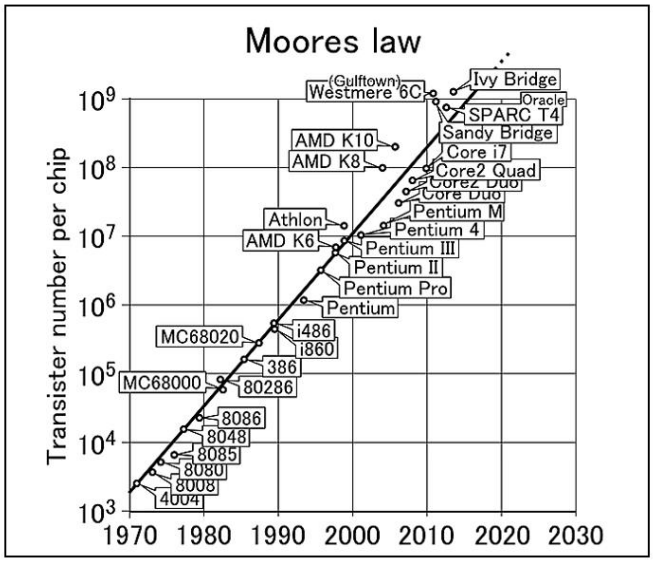


Figure 1. plot of CPU transistor counts against dates of introduction.(source [1])

RISE IN TEMPERATURE OF THE DEVICE DUE TO HEATING OF THE CPU

The currently available handheld devices use a multiprocessor SoC as their CPU. Although new thermal management techniques are introduced, the strain on MP-SoC is still increasing day by day. The need for more processing speed is going high. This causes the CPU to degrade over a time. Degradation of CPU is a process by which a CPU loses the ability to maintain an equivalent overclock, which can be sustained by increasing core voltage levels, is observed as a form of ongoing failure [6]. Overclocking refers to increasing the clock speed of the CPU in order to operate or process at faster speed. Each processor, regardless of silicon quality, is capable of sustained error-free operation while functioning within the bounds of the specified environmental tolerances (temperature, voltage, etc.) [6]. That means, rather than keeping the operation while functioning within the tolerances and increasing the sustainability, processors are configured to their highest achievable speed by applying no more than the process's maximum allowable voltage.

The myth, that overclocking is "safe" as long as we don't increase the processor core voltage is not true. With increase in frequency, the load temperature increases. This in turn reduces life of the CPU. Figure 2 shows degradation of CPU over the years. It clearly shows that the rate of degradation has increased due to rise in temperature.

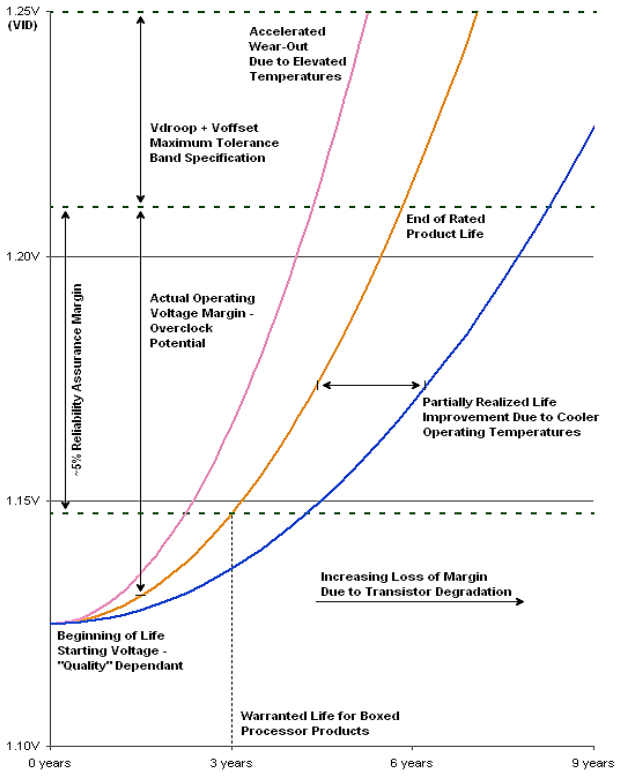


Figure 2. Degradation of CPU due to elevated Core voltage and temperature (source [6])

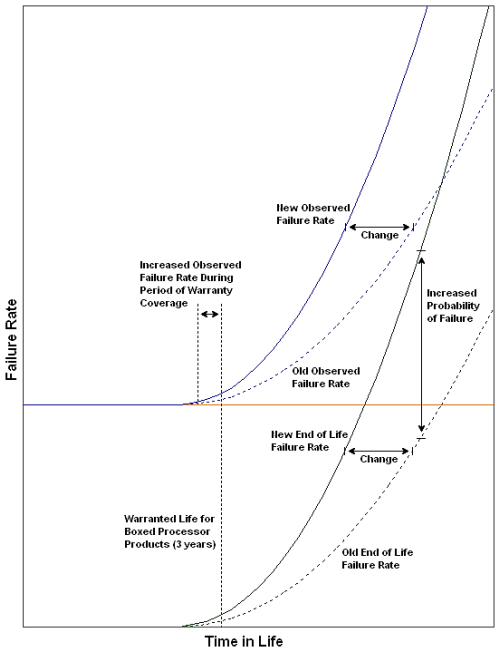


Figure 3. Failure Rate in the CPU (source [17])

RISE IN TEMPERATURE OF THE DEVICE DUE TO HEATING OF THE BATTERY

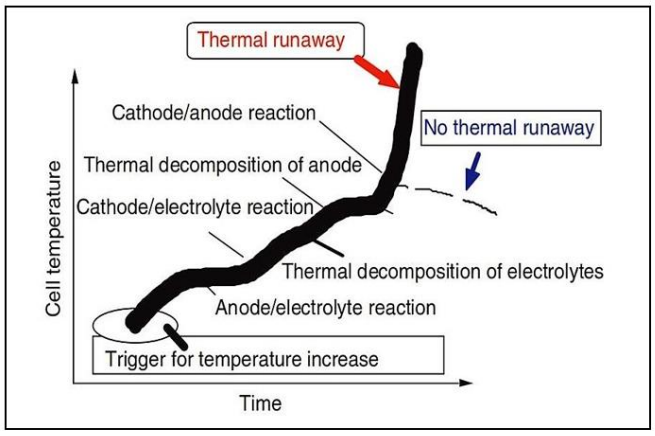


Figure 4. Thermal Runaway in a Cell of Battery

The increased thermal densities inside the Core of mobile devices can affect not only the CPU but also the peripheral components such as Batteries, Speakers, Camera module etc. Phone batteries are safe and give optimal performance around 20°C to 30°C. Most handheld devices have either a Lithium-ion battery or a Lithium-Polymer battery. After experimenting on different types of batteries at different temperature levels, it was observed that the Lithium-ions batteries were affected the most. These batteries tend to encounter a problem called 'Thermal Runaway'. 'Thermal Runaway', is a cumulative effect observed when the device heats rapidly and eventually ends up generating more heat than the maximum permissible value.

John C et al. defined thermal runaway as a phenomenon in which heating of battery causes even more temperature rises within the handheld devices, which ultimately leads the device to overheat [7]. If pressure builds up inside the battery, the battery could then swell, release toxic chemicals, or even explode. Temperature rise because of battery are mainly due to poor charging discharging cycles, bad power supply to the battery or prolonged use. The cause for rise in temperature due to the battery is approximately 30% and due to heating of Core/CPU is 70%. Hence, in this paper, we will focus mainly on rise in temperature due to CPU heating. The temperature variation in the device not only damages the components but also increases the power consumption over a period. In a study conducted by Gochman, they concluded that there is a constant need to develop new cooling methods for the heat dissipation in integrated chips [8].

As discussed before, in this paper, there are various reasons for temperature variations in the handheld devices. Few of them, as discussed before, are directly related to malfunctioning of either the CPU or the battery. In the handheld devices like mobiles and tablets, the components are closely packed. Many components take a very small space. Therefore, we cannot employ separate cooling techniques for individual components. Hence, we have to look for techniques which involve in cooling of the entire device. There are many ways in which a good thermal exchange can be achieved. The traditionally used methods include use of heat sink or heat spreaders. As the chips evolved further, these traditional methods fell short while managing the heat of these devices. This lead to more research in new thermal management schemes and the result was use of phase

change materials (PCM's), forced air convection, liquid cooling, cold plates etc. These newly discovered methods ruled the entire electronics industry for about a decade or so. Although these methods were convenient and had good thermal exchange efficiency, they fell short while meeting the expectations of the next generation technology. The new generation devices, such as mobiles and tablets needed quick cooling techniques. In this paper the author will be seeing various such techniques and will present a critical review upon concluding.

Survey of various thermal management techniques

Thermal management of a handheld device can be done with two methods i.e., with the help of Hardware, Software or both. Methods, involving hardware for thermal management, are termed as Passive or Static methods as once installed they cannot be altered at runtime. But, the new devices embedded with nanometer technology, require more adaptive techniques that can meet user requirements (thermal management) in the runtime. Hence, the new devices utilized software based schemes such as specially designed algorithm for runtime thermal management along with passive techniques.

The Thermal Management techniques mainly suitable for various types of handheld devices that use Multiprocessor SoC can be classified as:

A. Thermal Management with System Programming and Operating System:

Dynamic Thermal Management (DTM)

- ✓ Processor Throttling (Dynamic Voltage and Frequency Scaling (DVFS))
- ✓ Temperature-Aware Scheduling
- ✓ Thermal Herding
- ✓ Clock Gating
- ✓ Activity Migration

Temperature Management Unit (TMU)

Passive Thermal Management:

- ✓ Heat Spreader
- ✓ Heat Sink
- ✓ Heat Pipes
- ✓ Thermal Interface Materials (TIMs)

Active ThermalManagement:

- ✓ Forced Air Convection

Thermal Management with System Programming and Operating System:

Heat is generated in CPU is due to reasons such as high clock rates, improper execution of programs that cause deadlock, frequently restarting applications such as antivirus app etc. First rule of thermal management design is, "keeping cool starts from within". The processor chip is one of the main sources of heat within a smartphone. Hot spots can lead to power leakages, performance loss, and eventual degradation of the processor chip. As it is difficult to place a fan for cooling the processor in mobile, we need to employ software enabled techniques for thermal management.

1). Dynamic Thermal Management (DTM):

The Chip Multiprocessors (CMPs) have conquered the modern microprocessor market. With the reduced cost and complexity of designing thermal packaging, many Dynamic Thermal Management (DTM) schemes are being widely adopted in the modern processors as a useful technique to control CPU power dissipation.

DTM can be classified as (General Classification):

<u>Software Enabled</u> (Implemented only in software):
E.g. Temperature aware scheduling

<u>Hardware Throttling</u>:
Global Hardware Throttling:

Hardware support only for throttling the whole chip
Local Hardware Throttling :
Hardware support for throttling parts of the chip
Examples: Clock gating.

Hybrid Throttling:

Combinations of previous classes

The overall temperature of CMPs is highly dependent on the temperature of each core in the CMPs. Hence, the thermal model for uniprocessor environments cannot be directly applied in CMPs due to the potential heterogeneity. As shown in the figure 5, when the trigger occurs, DTM turns ON. The time difference between the occurrence of the trigger and the actual action taken is termed as 'startup delay'. The triggering event is a thermal sensor or a power estimator [9]. Once the trigger goes off, there is some initiation delay while an operating system interrupt and handler are invoked to interpret the triggering event.

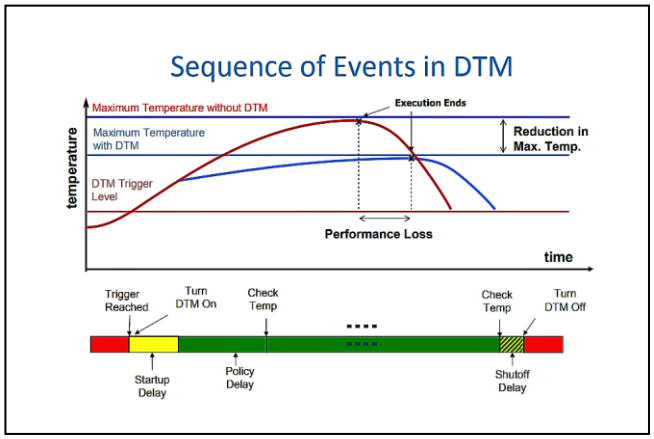


Figure 5. Sequence of Events in DTM

Once the handler has been executed, some DTM response begins. The response includes either voltage or frequency scaling. Depending on the type of response chosen, there may be some delay inherent in invoking it. This delay is termed as response delay. Once the response is in effect, the next issue concerns when to turn it off. Turning the response off as soon as the temperature dips below the threshold may not be good enough as the temperature may fluctuate around the threshold. Finally, once the DTM has determined that the response should be turned off; there is often a shut off delay while the voltage or frequency is readjusted.

There are various methods in which DTM can be implemented. Few are as follows:

Processor Throttling (Dynamic Voltage and Frequency Scaling (DVFS)):

CPU throttling is also known as Dynamic Clock or Dynamic Frequency Scaling (DFS). When the processes in the CPU are light, it runs at a lower clock speed and keeps the CPU cooler and uses less power, especially when combined with voltage throttling. This is because power used in a CPU is linear with clock frequency and voltage.

The dynamic power consumption can be calculated as,

$$P_T = C_{PD} * V_{CC}^2 * F_I * N_{SW} \quad \ldots. (1)$$

Here,

P_T	=	Transient Power consumption
C_{PD}	=	Power Dissipation Capacitance
V_{CC}	=	Supply Voltage
F_I	=	Input Signal Frequency
N_{SW}	=	Number of bits Switching

In CMOS circuits almost 70% of the dynamic power is consumed in the parasitic capacitance in their digital gates. Dynamic voltage and frequency scaling (DVFS) is a DTM method to optimize dynamic power consumption [10]. DVFS takes advantage of the relationship between speed and power consumption as a function of power supply voltage. (Refer equation (1).) The effect of CPU frequency and voltage is cubic. This is because power consumption has a linear relationship with input frequency and quadratic relationship with supply voltage. When some heavy (intensive) process is running and the CPU detect overheating, it automatically switches from a high

frequency clock source to a low frequency clock. There are only one or two clock sources in the architecture of currently available mobile CPU's. The desired frequency is derived using a set of frequency multipliers. When the temperature of the CPU comes back to the normal value, the clock frequency is regained. This process happens in the background. All these alterations are carried out dynamically while considering the real time CPU temperature. The performance may get affected for a certain time slot but not significantly. The FPS (Frames per Second) rate is reduces causing the graphics to slow down. Vinod Viswanath, in his article, explained that an efficient DTM system would reduce operating frequency and, at the same time, reduce the supply voltage [11]. This may affect the performance in terms of speed. Some example commercial implementations of dynamic voltage frequency scaling (DVFS) technology are Intel's SpeedStep and AMD's PowerNow. DTM / DVFS can be specifically used for handheld/portable/embedded systems i.e., in battery constrained devices. For example, AutoDVS, is a system for handheld computers that offers dynamic voltage scaling (DVS). AutoDVS not only lowers the amount of energy used but also ensures service quality by estimating user interactivity time, think-time and computation load, system-wide and for each program [11].

Temperature-Aware Scheduling

In the dynamic thermal management, microprocessor's temperature is controlled by the hardware that continuously monitors the chip temperature and reduces the processor's speed as soon as the preset thermal threshold is exceeded [12]. But practically, in real-time systems, all tasks are not the same. Some tasks take less CPU power, but a large amount of time. Some tasks are more CPU-intensive and generate more heat during execution. In the temperature aware scheduling, the tasks are executed according to their nature [13]. Each task is sorted according to its start time, deadline and heat contribution. Its working mechanism can be classified in three main steps as assuming, approaching and measuring. In the assumption stage, the program's hotspot behavior is characterized by intensity of its accesses to 'int' and 'fp' register files. Then the instruction from the thread that is likely to cool or less quickly heat the register files is approached. To detect thermal danger, the CPU temperature is sensed continuously. If we assume, at some step, the CPU temperature is **t**º C and a task is to be executed. Assume that the task has heat contribution **h**º C. Then the temperature T_N, at next step, after execution of the task can be given by,

$$T_N = (\mathbf{t} + \mathbf{h})/2$$

Therefore the temperature cannot exceed the thermal threshold T. Therefore, when the CPU hot, less intensive tasks are scheduled and executed. And when the CPU is cool, more intensive tasks are executed [13]. This helps in maintaining the temperature within the safety limits.

Thermal Herding

The embedded system developers have started producing products in 3D integration technology. 3D integration greatly increases transistor density while providing faster on-chip communication. Multiple cores can be embedded in a small space. 3D implementations of processors simultaneously provide increased device density, reduced latency and lower power consumption [14].

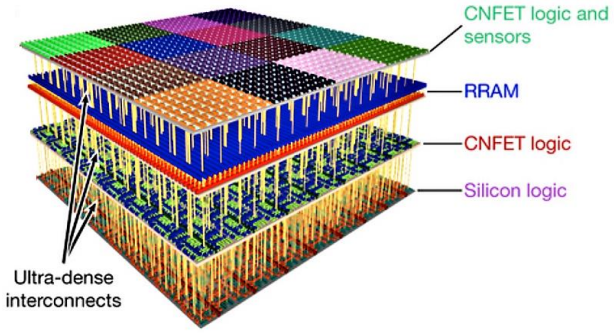


Figure 6. Vertically integrated 3D chip design(source [14])

However, 3D stacking of active devices on a single die increases power density. This increases thermal problems. In thermal herding, the multiprocessor activities are directed to the less heated area of the core. The traffic is diverted to another core if the existing core is heated or predicted to be heated [15]. Thermal Herding, also known as distributed traffic throttling, involves steering the traffic throughout the chipset to avoid hotspots. This reduces 3D power density and can be used to direct heat to the die closest to the heat sink in the chip. The major advantage of this technique is that the real time performance of the CPU does not degrade. But, on the other hand, this method is only applicable to the chips with on-chip networks.

Clock Gating

As we have discussed before in this paper, the power used in a CPU is linear with clock frequency. Hence, as the clock frequency increases, the power dissipation also rises. If the CPU temperature exceeds the thermal threshold, then immediate actions needs to be taken. Ideally speaking, the clock should be cut-off from the CPU in order to reduce power dissipation. The technique used, in which the clock is cut-off from the sequential circuits, is known as "Clock Gating". In the synchronous digital circuits, the clock is major cause for heat dissipation (up to 40-50%) [16]. Clock continuously consumes power as it keeps on toggling the registers. So, when the power consumption increases, the clock is shut off and the current state of CPU is maintained. Clock gating can be implemented by two ways i.e., 'Global Clock gating' and 'Local Clock gating'. In the global clock gating, the clock to the processors in the CPU is paused for few microseconds at a time. The cooling efficiency of Global Clock gating is about 70-80%. As it halts entire logic in the processor, the performance deteriorates. But the CPU cools efficiently [17]. As shown in the Figure 7, enable signal (EN) is necessary to generate a gated clock signal. The enable is made low when the clock is to be shut off. The output of latch and the clock signal are ANDed and the gated clock is provided to the registers in the CPU. When the EN is logic 1 CGIC output is passed on to the output. But when the EN is logic 0, CGIC output is gated i.e., clock is shut off thereby reducing the power consumption.

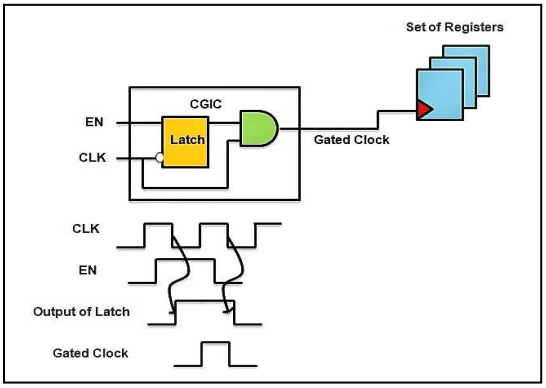


Figure 7. Clock Gating Integrated Cell (CCIG) (Source [16])

In the Local Clock gating, clock signal only of the desired core is shut off. Clock signal of the core which heats up more rapidly is shut off. This helps in sustaining the performance of the system. But, the cooling is not as efficient as Global Clock gating. The cooling efficiency of Local Clock gating is only 25-30% [17].

Activity Migration

In the processor, if some process is executing for a long time on a single computing unit, then there is high possibility of formation of localized hotspots. If these processes are switched between different computing units of the same processor then the chances of hotspot formation reduces significantly. Activity Migration is a specialized form of thermal management techniques in which the process or ongoing activity switches from one computing environment to another during its execution. This is also called as activity ping ponging. In the multicore processors, process migration is implemented using scheduling algorithm. It is easy for the multicore processors to switch or transfer the process through its

various units as the resources need not be changed (memory, files, and sockets).

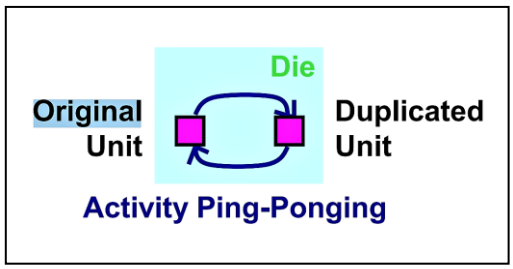


Figure 8. Activity Migration (source [18])

Process migration can be implemented in two ways:

a) ***Non-preemptive process migration***:

In non-preemptive process migration, migration takes place before the execution of process. In a process need not be preempted.

b) ***Preemptive process migration***:

In preemptive process migration, a process is first preempted then migrated and continues processing in a different computing environment.

The preemptive process is relatively expensive, since it involves recording, migration and recreation of the process state as well as the reconstructing of any inter-process communication channels to which the migration process is connected [18]. The non-preemptive process migration is relatively cheaper as relatively little administrative overhead is involved.

3) Temperature Management Unit (TMU)

A section presented by Se-Hyun Yang et al. described thermal management as a continuous process [19]. Their model consists of thermal sensors and a thermal management unit (TMU). Temperatures at various components are sensed using the thermal sensors and TMU records this temperature at every component so that it doesn't exceed the threshold called as throttling. If the TMU finds that a component has reached throttling point, it shuts off power supply to the related components till the temperature is settled down to an acceptable level.

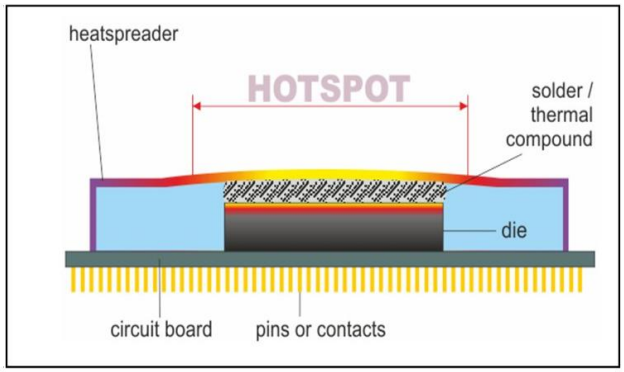


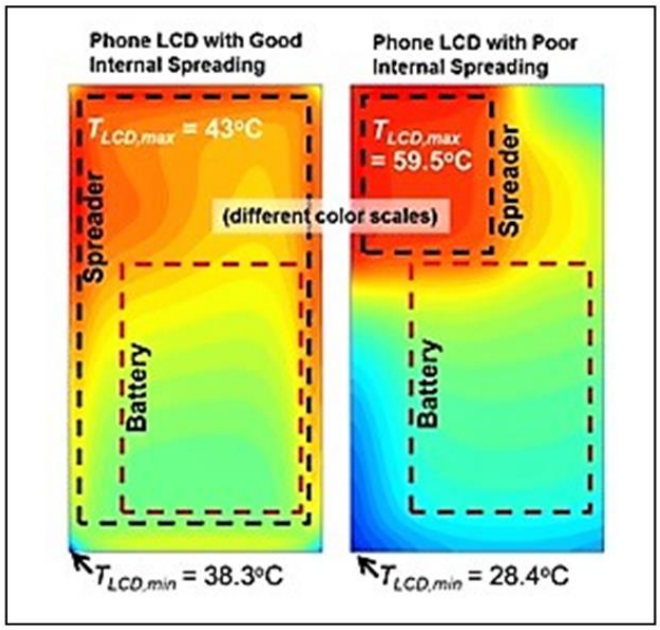
Figure 8. Typical Heat Spreader

B. Passive Thermal Management:

1) Heat Spreader:

Most mobile phones and handheld devices currently use a SOC or system on a chip that manages the device's operating system, memory, and microprocessor. These

Devices generate a significant amount of heat when operated for a prolonged time. Hence, the designer uses metal lids to direct the heat away from the SOC. The local area heating of the transistorized chip, also known as hot-spot, takes place in VLSI chips [20]. To minimize such type of heating, a thermally conductive foil is placed over the chip. Jaeho Lee et al. observed that by increasing surface area by 4mm could reduce the temperature by around 50C-250C. It acts as a heat spreader and reduces the effect of hot-spots [21]. The heat spreaders spread the accumulated heat over a large surface area. This results in faster cooling. Heat spreaders do not cool the CPU by themselves; they only transfer the heat to the outer environment where it can dissipate away from the processor without affecting the other components [22].



(a) (b)

Figure 9. Simulated temperature distributions on the surface of a generic phone (138 mm x 70 mm) for two different thermal management schemes. (a) Large heat spreader (128 mm x 62 mm), which couples the battery with the heat generating chips and yields a more uniform temperature. (b) Smaller heat spreader (35 mm x 33 mm) yielding highly nonuniform LCD temperature. (source [23])

As shown in the Figure 2, Heat Spreader is placed over the die. It spreads the accumulated heat, at a certain hot spot, over a large surface area. According to the principle of heater spreader, it spreads over a larger area than the chip. Hence, they occupy more space on the PCB. Therefore, applications where circuit area is a major constraint, heat spreaders may not be a good choice. Heat sinks are known for their performance as they are noiseless and cost effective. Heat spreaders can also be combined with a heat sink for a better performance. Victor Chiriac et al. (Figure 2(a) & 2(b)) illustrated that phone thermal design must meet certain skin limit temperatures and avoid the formation of hot spots [23]. The poor heat spreading on the device surface leads to a peak temperature of 59.5°C (Figure 2(b)), violating the 45°C skin temperature limit specifications set for the current design. By improving the thermal spreading, the peak temperature drops below the critical limit (Figure 2(a)).

Heat Sink:

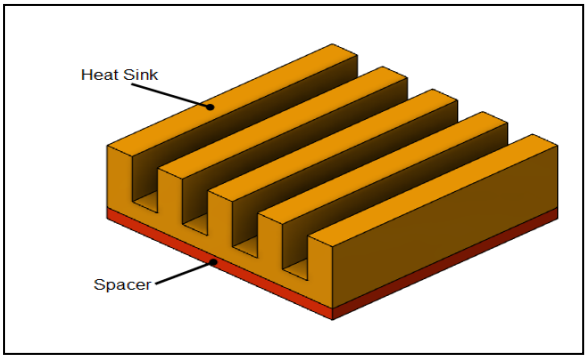


Figure 10. Typical Heat Sink

Heat sinks are used dissipate heat from the processor out into the surrounding air. They absorb the heat and dissipate it to the environment. Similarly, to control the heat accumulation in an Integrated Circuit package, a metal block or shield which acts as heat sink, is mounted on top of die [22]. Chien-Cheng Lee et al. carried out an experiment, in which a metal coin was inserted into PCB to dissipate the generated heat. Metal coin was mounted on PCB under some high power components like power transistor [24]. Yin Xiong et al. conducted experiments with very thin heat spreaders made of Graphite. Graphite was used because of its unique anisotropic properties of high in-plane thermal conductivity and low thickness thermal conductivity [25]. Size of heat sink varies according to the heat flux density of the component.

Heat Pipes:

Another way to transform a heat spreader into a cold plate is to use heat pipes. A fluid is used to enhance heat exchange between two surfaces. Samsung already succeeded using water filled copper pipes in their S7 devices, as well as their S8 and S9. Though this method is efficient, it is costly.

Thermal Interface Materials (TIMs):

There are various materials that have a good thermal conductance i.e., they have the ability to absorb heat faster than others. They are available in various forms such as tapes, grease, paste, liquid solution, phase change materials, heat pads etc. They are used with heat sink or heat spreaders to enhance heat transfer.

Active Thermal Management :

Forced Air Convection:

Air is one of the best coolants. Air is directly subjected to the heat prone area with the help of fans. This method is known as active cooling technique. These generally have a fan or blower of some kind. But, in handheld devices, space is major constraint [26]. The initial proposed design was too large to fit in a handheld device such as PDA or a mobile phone Yoshiharu Iwata et al. proposed a new outline design method for layout design of handheld device package [27]. It is shown in figure 12.

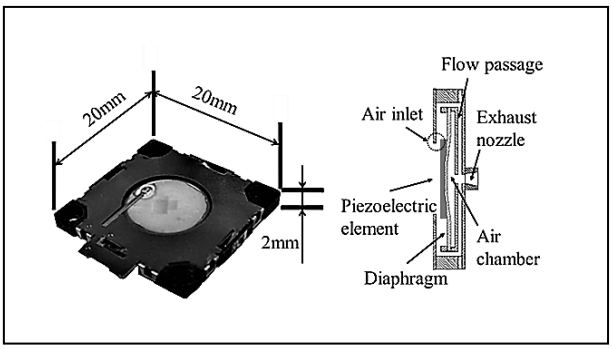


Figure 11. Piezoelectric Micro- Blower Fan-sink

TABLE 1. COMPARISON OF COOLING TECHNIQUES

Methods / Parameters	Small In Size (For *um* and *nm* Technologies)	High Cooling Efficiency	Rapid Rate Of Cooling	Least Effect on Performance (processing activities)	Cost Effective	Simple Design
Processor Throttling	✓				✓	
Temperature-Aware Scheduling	✓	✓	✓			
Thermal Herding	✓	✓				
Clock Gating	✓		✓		✓	✓
Activity Migration	✓					
Temperature Management Unit (TMU)	✓		✓			
Heat Spreader		✓		✓		✓
Heat Sink		✓		✓		
Heat Pipes		✓		✓		
Thermal Interface Materials (TIMs)	✓			✓	✓	✓
Forced Air Convection				✓		

II. REVIEW

In this paper many possible ways for efficient heat transfer for handheld devices have been discussed. As the author have discussed, in the handheld devices like mobile and tablets, the size of chipset is shrinking. This is done in order to ensure that many components fit in a small space thereby reducing the size and overall cost of the device. As we pack multiple computing elements on a single die, the problem of hot spot arises. As the number of hotpot rises, the life of CPU degrades. To deal with such conditions a proper heat transfer mechanism should be implemented.

Table 1 shows comparison of thermal transfer methods. As the DTM techniques are software enabled, they take very less on chip area. But, these techniques do occupy memory. The passive cooling techniques, except the use of TIMs, take large chipset area. If compared on the basis of cooling efficiency, temperature aware scheduling and thermal herding are found out to be the best techniques. Also, the heat sinks and heat spreader do perform well. Hence, they also have a high cooling efficiency. Cooling efficiency is not only dependent on the rate of thermal transfer, but also the ability to keep the device cool for long hours.

If compared on the basis of rate of cooling, the temperature aware scheduling, thermal herding and TMU can be the best option. In temperature aware scheduling, the processes are executed according to their priority and by the amount of heat they contribute while executing. Hence, before the execution of any task, the care for keeping the CPU cool already has been taken. Similarly, in the TMUs, power supply to the related components is shuts off till the temperature is settled down to an acceptable level. Hence, these methods have highest rate of cooling. While using any of these cooling methods, the CPU performance should be least affected. In the software enabled techniques, the performance in terms of speed and throughput is affected significantly. Here the heat spreaders, heat sink and heat pipes perform better as they do not interfere with the CPU's processing activities. While designing any system, the designer has to think about the cost effectiveness. If compared on the basis of cost effectiveness, the techniques such as clock gating, processor throttling and use of TIMs are found to be the best. These techniques require minimum number of resources and hence, they are cost effective. However, the design complexity of clock gating, heat spreader and TIMs is less. This makes it easier to implement thereby reducing the system complexity.

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