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Cooling Techniques and Power Throttling for Mobile Processors: A State-of-the-Art Review

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Abstract
Mobile processors have now become very integrated system-on-chip (SoC) platforms with the ability to support heterogeneous workloads (such as multimedia, gaming, machine learning inference, and 5G communication). This development has the price of more power density, which produces a lot of heat in small devices without active cooling. Thermal management therefore has emerged to be a critical area of mobile device design, with impact on longevity, energy efficiency and long-life performance. To ensure safe operating temperatures, modern mobile SoCs are very dependent on the use of power-throttling techniques, including dynamic voltage and frequency scaling (DVFS), thermal-conscious task scheduling, power capping, and core-level gating. Passive cooling methods such as thermal interface materials, heat spreaders, vapor chambers, phase-change materials, and graphite/graphene sheets are also important components of the heat dissipation and hotspot solutions along with software-based solutions. In this paper, the authors provide a review of the current state of the art in the field of cooling methods and dynamic thermal management systems, evaluating their efficiency, constraints, and interactions. Moreover, it focuses on co-optimization of hardware and software solutions as a solution to maintain high performance and thermal safety.

Keywords: *Thermal Management, Power Throttling, Mobile Processors, Passive Cooling, Dynamic Thermal Management (DTM), System-on-Chip (SoC), Heat Dissipation*

I. Introduction

Contemporary mobile processors have significantly changed into highly integrated system-on-chip (SoC) platforms that can handle heterogeneous workloads like real-time multimedia, mobile gaming, machine learning inference, and 5G communication. While the increase of core counts, GPU capabilities, and NPU accelerators goes on, the consequent increase of power density leads to a large amount of heat in thermally constrained mobile devices. In contrast to desktops, mobile systems are without active cooling fans, hence, thermal build-up is the main factor that directly limits sustained performance [1], battery efficiency, and device reliability in the long run. As a result, thermal management has been at the centre of co-design across architecture, materials, and system software layers.

In order to keep the temperature within limits that are safe for the device under variable load, contemporary mobile SoCs resort to power-throttling mechanisms that are considered as the first line of defence, almost exclusively. Through power capping, thermal-aware task scheduling, dynamic voltage and frequency scaling (DVFS), and core-level gating, the electrical activity of compute units is dynamically controlled in accordance with the thermal condition derived from the real-time feedback. These mechanisms, although they do not let the device get out of hand thermally, have to make a concession with the peak performance, hence, in most cases, one can observe a drop in performance during long periods of high-intensity workloads [2]. Therefore, the effectiveness of power-throttling strategies is, to a great extent, dependent on the thermal properties of the device's physical cooling system.

Cooling innovations for mobile processors need to happen alongside technological improvements to mobile processors if want to be able to cope with the limited space for the compact form factors. More and more mobile platforms are using graphite heat spreaders, vapor chambers, phase-change materials (PCMs), micro heat pipes, and even high-conductivity thermal interface materials (TIMs) in order to accelerate heat diffusion and get rid of localized hotspots. These physical means have an immediate effect on how severe power-throttling policies can be: a better heat removal capacity means that higher sustained power envelopes can be achieved and the incidents of thermal throttling being triggered can be reduced [3]. Therefore, cooling solutions and power-management techniques are two closely intertwined elements of a single integrated thermal management system.

In sum, the heat dissipation of mobile CPUs results from complex interplay of the chip architecture generating the heat, software-controlled throttling and hardware cooling structures [4]. Grasping this mutual dependence is the main point of engineering the future generation of the mobile platforms which able to maintain high performance thermal safety as well as the user experience intact. This paper interrelates the latest innovations in these fields and points up the system-level co-optimization phenomena as a way forward stage of mobile computing.

A. Structure of the Paper

This is a review that is systematic and is on thermal management in mobile processors. Section II discusses the thermal basics of mobile processors such as heat generation. In section III, the passive cooling methods are described. Section IV discusses such dynamic thermal management schemes as DVFS and thermal-aware scheduling. Section V gives the literature review of the more recent developments and Section VI concludes by giving the way forward in the research.

II. Thermal Fundamentals of Mobile Processors

Heat is the by-product of the mobile processors and it is generated in transistors of switching, leakage currents and some other components (GPU, radios, etc.). The processors are highly dense and are packed in a small form-factor (smartphones, tablets) thus the produced heat is not easily dissipated; hence thermal conduction through the silicon die, internal heat spreaders/thermal interface materials, and the device casing becomes the main way of heat dissipation [5]. These temperatures at a junction and on a surface can be increased by sustained workloads without active cooling (like fans), thus the thermal throttling is activated, performance is reduced, battery life is shortened, and even long-term reliability is affected. The right thermal design and dynamic thermal management including power control, workload scheduling, and use of efficient heat spreaders are very important to keep temperature at a safe level and maintain user comfort.

A. Heat Generation Mechanisms in Mobile SoCs

A major source of heat in mobile SoCs is dynamic power consumption. When one or more of the CPU, GPU or other cores are switching and performing computation, they also cause heat dissipation due to their switching activity [6]. Besides that, static (leakage) power is becoming noticeably non-negligible. In other words, as the temperature goes up, the leakage current increases exponentially, and so, a positive feedback loop formed between power dissipation and temperature. On top of that, in real devices, the heat generation is not only from the SoC.

B. Thermal Behavior and Performance Trade-offs in Mobile Processors

High thermal limits are formed as a result of dense integration on mobile processors that produce high heat and thus performance is affected [7]. Hotspots are active areas, which lower the efficiency and reliability of power. Heat spreads across the layers of the device and bad spreading exacerbates thermal conditions.

- **Thermal Constraints:** Mobile processors have severe thermal requirements which are to be followed to avoid hardware damage and to make the users comfortable. Junction temperatures are often limited to hard-to-reach areas such as 85-90, and surfaces of devices must not be more than the human comfort limit (~45). When these limits are exceeded, protective mechanisms, including dynamic throttling, shutdown of core of power capping, activated to limit performance to ensure safe operation [8].
- **Hotspot Formation**: High intensity workload concentrates the power consumption in the specific locations like CPU cores, GPU clusters and AI accelerators, creating a localized hotspot**.** All these causes these areas to heat quicker than the chip around them, large thermal gradients to develop, leakage currents to rise, and energy efficiency to decrease. Hotspots may also accelerate the ageing of components and cause these to thermal throttle sooner.
- **Heat Propagation**: Heat is conducted out of the silicon die by thermal interface materials and heat spreaders which eventually diffuse to the casing and surface of the device. The effectiveness of heat transfer is based upon the characteristics of materials, stack-up of devices, and air gaps [9]. The reason why poor heat spreading results in hotspots that cannot be eliminated by the time the average chip temperature enters the safe range is that thermal-aware design is important.
- **Impact on Performance**: Gaining power enhances performance, but increases temperature and consequently, leakage current and decreases energy efficiency [10]. This nonlinear dependence implies that high temperatures may decrease the useful performance that may be obtained by the identical power budget. Some of the strategies to balance thermal safety and performance include DVFS, thermal-aware scheduling and core-level throttling, which are applied in mobile systems.

A. Thermal Design Issues in Mobile Processors

Compact designs, inadequate cooling, power-dense components and mechanical constraints are the causes of thermal challenges faced by mobile processors, which must cool efficiently to maintain performance, reliability and user comfort.

- **Mechanical Stack up:** The z direction of mobile devices is severely limited, and the entire thickness is usually kept below 1 cm. Mechanical stack-up. The stack-up is standard and starts with the display panel, the display and touch layers, and is approximately 4 mm thick [11]. Below it is the mid-frame or chassis, which gives it structural rigidity at approximately 1 mm. Another 2 mm is occupied by the chip and PCB assembly, and the outer skin of the device, or plastic cover, would take approximately 1 mm. Lastly, a 1 mm air gap is given to take into consideration mechanical tolerances. The entire stack-up determines the physical design limits as well as the thermal path in which the heat has to be transferred within the device.
- **Temperature Limits:** Mobile processors produce heat depending on the workload, and their junction temperature should not exceed the package limit, generally in the range of 85 -90 o C. Due to the thinness of the mobile devices, active cooling (such as fans) is not possible and thus the heat is dissipated by conduction to the device case. In this path, thermal resistance is low then it keeps the chip cooler [12]. The heat eventually gets to the outer surface of the device, which should not be exceeded by a safe limit of skin temperature to guarantee the comfortability of the user. Surpassing such a level renders the phone difficult to hold, which is the thermal comfort limit of mobile designs.

- **Mechanical Tolerances:** In the design of mobile devices, mechanical tolerances have become crucial, especially given their tiny size. These tolerances can create tiny air gaps and are found all throughout the device stack-up in situ, including between the mid-frame and the display screen. The air in such gaps is stagnant and therefore conduction becomes the primary method of transfer of heat. There is no thermal conductor in the air and therefore bigger air gaps in between the parts of the device ensures heat gets trapped in the device thus heating up the components and lowering the performance of the device [13].
- **Power Sources:** There are different parts that dissipate power in a mobile device, and power map also varies with task or application. The processor, Wi-Fi module, PMIC and display LEDs are major heat generating components. Since these elements are normally close to each other, they create a concentrated heating area. This causes adjacent chips to overheat one another resulting in thermal accumulation and possible performance throttling.

III. Passive Cooling Techniques

Passive cooling of mobile processors depends on materials, geometry and physical principles (conduction, phase change, radiation) as opposed to active and power-intensive components (e.g. fans). These methods seek to either dissipate or evenly redistribute heat out of the chip to other device components, to avoid thermal throttling and to continue operation at normal load [14]. The important passive techniques include those that are discussed below.

A. Thermal Interface Materials and Heat Spreaders

In mobile devices, the heat is conducted out of the processor die by thermal interface material (TIM) or heat spreaders that constitute the main conduction pathway. TIMs are used to reduce contact resistance in that microscopic irregularities on the die-spreader interface are filled using high-conductivity heat spreaders (copper, aluminum, graphite, or graphene sheets), and the heat spreads laterally through the device. Their performance is determined by intrinsic thermal conductivity, mechanical compliance, thickness and stability over a period of time when subjected to repeated thermal cycling [15]. Optimized TIMs with effective heat spreaders enable lowering of maximum junction temperatures, thermal hotspots, stability of systems, and enable mobile processors to be able to perform well even at high workloads without being throttled aggressively.

B. Vapor Chambers and Heat Pipes

Passive two-phase cooling, vapour chambers, and heat pipes have wide use in modern mobile processors as devices to address high heat flux in small form factors. These machines heat up the processor hot spot by evaporating a working fluid and letting the vapour diffuse throughout the chamber condensing on the cooler surfaces and flowing back to the source through capillary effect using a wick structure. This results in an extremely low thermal resistance, uniform temperature distribution, and rapid device heat dissipation [16]. Vapor chambers have been found to be effective in high-performance SoC smartphones, phones with game capabilities, and phones with 5G connections, allowing them to operate more intensively on heavy workloads without overheating surfaces and slowing down their performance.

C. Phase-Change and Material-Based Cooling Enhancements

Phase-change materials (PCMs) possess large abilities to acquire and free colossal amounts of latent heat throughout solid liquid boundaries, which proactively offsets momentary temperature spikes in mobile processors. To address the low thermal conductivity intrinsically linked to most cooling designs, the current designs incorporate material additions in the form of metal foams, porous, or fins, or composite PCM matrices as a way of increasing the speed at which heat is transferred [17]. These hybrid systems correct temperature gradients, lower peak temperatures, and permit passive or semi-passive cooling of high-powered SoCs without large active cooling subunits and thus can be used in the small smart phones and tablets.

D. Graphite and Graphene-Based Heat Spreaders

Graphene and graphite sheets are thin, bendable, and lightweight heat conductors of high in-plane thermal conductivity, which are intended to distribute the hotspots of processors laterally over the device frame [18]. They are also relatively beneficial in mobile devices, where space usage is constrained, and they effectively achieve passive cooling without contributing thickness or mass, as well as being commonly used in smartphones along with TIMs and vapor chambers to improve spreading of heat, minimize hotspots, and keep the SoC performance constant over full workloads, e.g. during gaming, 4K video handling, or 5G data transfer.

IV. Power Throttling and Dynamic Thermal Management

Temporal thermal control and power throttling are key methods in current mobile and embedded processors, which are aimed at sustaining stability and optimality around the system, as well as avoiding hardware damage caused by overheating. With the continued increase in the power of processors, but the reduction in size, heat and power management has become a critical application to guarantee the ease of operation and increase the device longevity.

A. Dynamic Voltage and Frequency Scaling (DVFS)

Dynamic Voltage and Frequency Scaling (DVFS), a crucial power-management technique for mobile CPUs, reduces power by slowing the clock speed and voltage, which is proportional to the square of the voltage. DVFS increases or decreases these parameters based on work load, saving energy when the load is low, and restricting heat when the load is high. It is also an early thermal-protection system, which automatically reduces the frequency when temperature indicators sense an increase in temperature [19]. Although this is more efficient and increases battery life, it causes a performance thermal trade-off whereby the system does less to remain within safe limits. The current generation processors are based on integrated power-management unit (PMU) reading workload and thermal measurements and adjusting voltage and frequency dynamically. This can be pictorially illustrated as seen in Figure 1 where the voltage, frequency, power, and performance become less effective when the thermal threshold has been reached and power throttling takes effect.

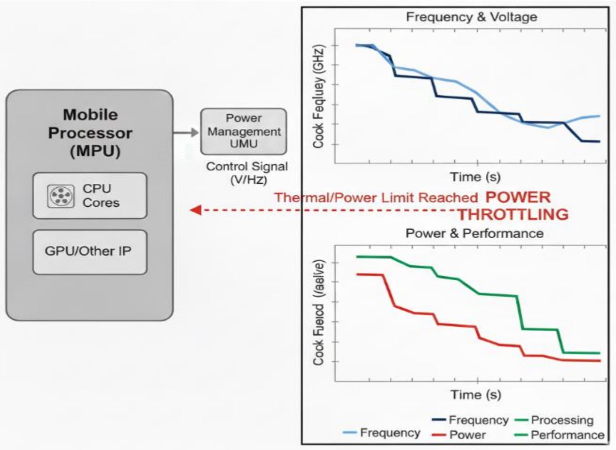

Fig 1: Dynamic Voltage and Frequency Scaling (DVFS) Mechanism for Power Throttling in Mobile Processors.

A. Thermal-Aware Scheduling and Core Migration

Thermal conscious scheduling and core migration assign tasks according to temperatures and not performance. The system avoids the occurrence of hotspots and distribution of temperature by migrating workloads to the cooler cores and keeps temperature distribution more homogeneous. This contributes to a higher level of stability, less thermal stress, and higher long-term reliability, particularly in those devices with low cooling capacity. How thermal-aware scheduling and core migration work, why it is important, and what the benefits of these techniques are explained below:

- Allocates workload according to core temperature so that the workloads are kept in cooler regions of the chip to ensure safety in operation.
- Core migration eliminates long hotspots, which concentrate heat in the processor, and evenly distributes it to stop thermal accumulation.
- Takes real-time or approximate thermal data, which enables the system to make the right scheduling decisions that safeguard the processor [20].
- Can be used successfully with DVFS which minimizes total heat with manages heat distribution controlled by scheduling.
- Reduces thermal wear on a long-term basis enhancing the life and durability of the cores in the processor.
- Very well applicable to mobile and embedded environments, where cooling facilities are available only to a limited degree and thermal control has to be more software-based.

A. Advantages of Thermal Management in Mobile Processors

There are multiple key advantages of thermal management in mobile processors, as it guarantees the best performance, energy efficiency, and reliability over time, as well as safeguards the hardware against overheating and thermal stress.

- **Increased Stability of Performance:** Thermal management ensures high levels of performance are maintained within the processor when it is heavily loaded as it is able to control temperature before it throttles.
- **Improved Energy use:** Techniques such as DVFS and workload adaptation make power usage more efficient and minimized the use of unnecessary energy and increased battery life [21].
- **Extended Hardware Lifespan:** By increasing the hardware lifespan, there is minimal thermal stress on the processor and other components, and improve the overall durability of the device.
- **Prevention of Hotspots: Core migration and workload distribution:** Core migration and workload distribution ensure that the temperature of the processor remains even without any localized hotspots which can reduce performance or cause component damage.

V. Literature Review

Researchers have been improving various thermal and power throttling techniques such as intelligent agents, instruction-level throttling, app-aware control, and predictive DTPM, to help these systems to be more temperature, power, and thermal violations efficient.

Dey et al. (2019) In order to monitor and lower the system's operating temperature by controlling the CPU cores' running frequency while simultaneously meeting performance constraints, an intelligent software agent collaborates with other resource mapping and partitioning mechanisms. When compared to the state-of-the-art techniques, the suggested method, Deadpool thermal management agent, may lower the system's total operating temperature by 24.21% and reduce thermal cycle by a maximum of 67.42% [22].

Owahid and John (2019) The fetch throttling for the top 10 instructions that cause frequent pipeline delays is determined by instruction profiling. The early pipeline stages' throughput places a cap on the throughput of all later stages in superscalar processors. Maintaining the maximal instruction fetch bandwidth is therefore necessary to attain excellent performance. Because of the aggressive fetching of the instruction cache, this results in increased power consumption, which is frequently squandered. This study uses instruction profiling to construct fetch throttling in order to solve this issue. The instruction profile shows the likelihood that each pipeline stage's instructions may stall [23].

Park, Lee and Cha (2018) an app-oriented heat management system that precisely limits background apps in order to maintain front applications' frame rates. created a model that forecasts each application's heat contribution based on hardware utilisation for effective thermal management. Each background application's system resources are progressively limited by the suggested system based on how much heat it contributes. The plan was put into practice on a Galaxy S8+ smartphone, and a comprehensive assessment confirmed its value [24].

Bhat et al. (2018) A DTPM algorithm, which is based on system identification and employs a useful temperature forecast approach. The suggested approach uses the anticipated temperature to dynamically calculate a power budget. With little effect on system performance, this budget is used to restrict the frequency and number of cores in order to prevent temperature breaches. two distinct octa-core bigs for the experimental measurements. The suggested method forecasts the temperature with less than 5% inaccuracy across all benchmarks, as shown by LITTLE CPUs and popular Android apps. Using this prediction, the suggested DTPM method effectively controls the maximum temperature, reduces temperature violations by an order of magnitude, and, when compared to the default approach, lowers the average overall power usage by 7% [25].

Lee, Kim and Shin (2017) presents a thermoelectric cooling system that makes it possible for mobile devices to handle CPU heat effectively. The objective is to effectively use thermoelectric cooling to reduce performance loss due to thermal throttling. The system adaptively regulates cooling power at runtime because mobile devices encounter significant fluctuations in workloads and ambient temperature. The performance reduction from the maximum speed is just 1.8% with the TEC compared to 19.2% without the TEC, according to a study on a smartphone utilising mobile benchmarks [26].

Li and Mishra (2016) This study tackles the problem of controlling power consumption in multicore smartphones using a middleware layer that schedules the ideal number of cores for running programs while considering the trade-off between user experience, performance, and power consumption. The study examines the effects of scheduling seven distinct well-known programs across one to four cores on the overall power consumption after outlining a straightforward and precise technique for measuring it. These techniques significantly reduce power consumption while maintaining high performance and user experience, according to evaluation from a prototype implementation of the middleware on a quad-core HTC One [27].

Table I presents a consolidated overview of recent studies on cooling techniques and power-throttling mechanisms for mobile processors, highlighting their focus areas, methodological approaches, key findings, existing challenges, and proposed future research directions.

TABLE I: SUMMARY OF RECENT STUDIES ON COOLING TECHNIQUES AND POWER THROTTLING FOR MOBILE PROCESSORS.

Reference	Study On	Approach	Key Findings	Limitations	Future Directions
Dey et al. (2019)	Intelligent thermal management for mobile processors	Deadpool thermal management agent regulating CPU core frequency using resource mapping and partitioning	Reduced overall operating temperature by 24.21% and thermal cycles by 67.42%, outperforming state-of-the-art	Focused mainly on CPU regulation; limited exploration of GPU or heterogeneous components; may not generalize across diverse workloads	Integrate with heterogeneous SoCs, explore adaptive learning-based frequency scaling, expand evaluation to real-world multi-app workloads
Owahid & John (2019)	Power dissipation and performance optimization in superscalar processors	Instruction-profiling-based fetch throttling for top stall-causing instructions	Reduced unnecessary power dissipation by avoiding aggressive and wasteful instruction fetching	Approach heavily dependent on accurate profiling; may not respond well to dynamic workload shifts; limited thermal perspective	Combine thermal-aware profiling with ML-driven instruction stall prediction; extend to mobile heterogeneous pipelines
Park, Lee & Cha (2018)	Thermal management of smartphones with multi-app environments	App-oriented scheme restricting background apps based on predicted heat contribution	Maintained foreground FPS while reducing thermal load from background apps; validated on Galaxy S8+	Focuses primarily on app-level behavior; does not directly regulate hardware DVFS; may not scale to future multi-tasking demands	Integrate with system-level DVFS; employ real-time learning models; generalize to various OS platforms
Bhat et al. (2018)	Dynamic Thermal and Power Management (DTPM) on mobile big.LITTLE processors	Temperature-prediction-based algorithm using system identification to compute dynamic power budgets	Achieved <5% prediction error, reduced temperature violations by an order of magnitude, decreased power consumption by 7%	Requires continuous prediction and tuning overhead; may struggle under highly unpredictable workload spikes	Incorporate deep learning-based predictive thermal models; extend to sensor-rich devices; improve multi-core coordination
Lee, Kim & Shin (2017)	Thermoelectric cooling (TEC) for mobile processors	Runtime adaptive thermoelectric cooling to minimize thermal throttling	Reduced performance loss to 1.8% with TEC vs 19.2% without; demonstrated significant cooling effectiveness	TEC increases device weight, cost, and power consumption; not ideal for ultra-compact devices	Develop ultra-low-power TEC modules; hybrid cooling combining TEC and software DVFS; explore nano-material-based TEC solutions

Li & Mishra (2016)	Power management in multicore smartphones	Middleware scheduling optimal number of active cores based on usage, power, and user experience	Significant power reduction while maintaining user experience; validated on HTC One	Middleware overhead may impact latency; limited to core scheduling only; no direct thermal modelling	Combine with thermal prediction engines; integrate GPU/core coordination; incorporate user-context awareness for smarter scheduling

VI. Conclusion and Future Work

Cooling techniques and power-throttling mechanisms are essential to maintaining optimal performance, energy efficiency, and reliability in modern mobile processors. Effective thermal management combines passive cooling methods, such as advanced thermal interface materials, vapor chambers, phase-change materials, and graphite or graphene heat spreaders, with dynamic strategies like DVFS, thermal-aware scheduling, and core migration. These approaches work in tandem to dissipate heat efficiently, prevent hotspot formation, and ensure safe device operation without compromising compact form factors. Studies show that integrating predictive algorithms, app-aware control, and intelligent thermal agents can significantly enhance temperature regulation and reduce performance losses during sustained workloads. However, challenges persist in managing heterogeneous workloads, improving predictive accuracy, and minimizing performance trade-offs while maintaining user comfort. Future research should emphasize the co-design of hardware and software for thermal management, exploring machine learning-driven predictive models, hybrid cooling solutions combining passive and active techniques, and real-time adaptive control for heterogeneous SoCs. Advancements in these areas can lead to mobile platforms capable of sustaining high computational performance, extending battery life, and ensuring thermal safety under diverse and intensive operating conditions, ultimately improving the overall user experience and device longevity.

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