2019 International Conference on Mechatronics, Robotics and Systems Engineering (MoRSE)
4-6 December 2019, Bali, Indonesia

Analysis of Power, Temperature, and Performance on Mobile Application Processor

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***Abstract*—Recent mobile devices have multiple cores and high operating frequencies. As a result, their performance has increased, along with their power consumption and temperature, which have become problems to solve. To understand how to operate a CPU efficiently while solving these problems, we study the relationship between power consumption, temperature, and performance as functions of the number of operating cores and operating frequency. We use CPU power consumption that we measured, use steady-state temperature of the CPU calculated by Therminator and use DMIPS that is an index of CPU performance measured by Dhrystone. The experimental results show that the performance increases and temperature decreases as the number of operating cores increases for the same power consumption. In addition, for the same performance, power consumption and temperature decrease as the number of operating cores increases. Consequentially, the quad-core shows a 75.54% performance improvement and 36.04% reductions in temperature compared to the single-core for the same power consumption. In addition, when at the same performance, the quad-core has decreased power consumption and temperature compared to the single-core, 49.42% and 53.94%, respectively. Therefore, operating by increasing the number of cores in the multi-core application processor will effectively increase the performance and lower the power consumption and temperature.**

***Index Terms*—CPU, multi-core, power consumption, thermal, performance, mobile application processor**

I. Introduction

Due to the high-performance demands for smartphones, the number of operating cores and frequency are increasing. The first smartphone had single-core 1 GHz processors, but the latest one is an octa-core 2.7 GHz with an increased number of cores and operating frequency. Thus, smartphones can do many things like calling, texting, surfing the web, and playing games or 3D content that have high-performance demands.

However, increasing the number of operating cores and frequency leads to power and thermal issues in mobile devices [1]. Therefore, it is important to manage power and thermal problems [2]. Mobile devices pack many parts into a limited space; in particular, the size of the battery is fixed. Therefore, increasing power consumption leads to decreased usage time. In addition, as the power consumption increases, the temperature of the mobile device increases [3]. If the temperature of a mobile device is increased, its stability and safety are not guaranteed. Therefore, it manages the temperature in various ways [4]. For example, when the temperature is high, the mobile device limits the operating frequency and turn off the cores to lower the temperature. However, this also decreases the performance of the mobile device.

As mentioned before, the increase on the number of operating cores and frequency will also increase the power consumption and temperature problems. Therefore, to solve these problems and find the efficient CPU operating method, we studied and analyzed the relationship between the two in terms of the number of cores and operating frequency.

The rest of the paper is organized as follows. Section II gives backgrounds that are needed to understand the conducted experiment. Section III explains the thermal simulator. Section IV describes the experimental environment while Section V shows the analysis of power, temperature, and performance of the multi-core system. Section VI concludes the paper.

II. Background

A. Application processor

The application processor is an important component in smartphones. It operates the operating system, runs applications in the mobile operating system environment, and controls various system devices and the interface. The application processor is a system-on-chip that consists of a CPU, GPU, modem, VPU, DSP, and many other components, as shown in Fig. 1 [5]. The CPU performs arithmetic and logic operations or data processing, the GPU processes 2D and 3D graphics work, the modem connects to the Internet via 4G and Wi-Fi, the VPU plays ultra-high-definition (UHD) content, the DSP processes digital audio and video signals. Among the application processors, the CPU performs important functions for the smartphone and its performance depends on the type, speed, and the number of cores. In addition, it is also the most power-consuming component of the smartphone [6].

978-1-7281-3984-5/19/$31.00 2019 IEEE

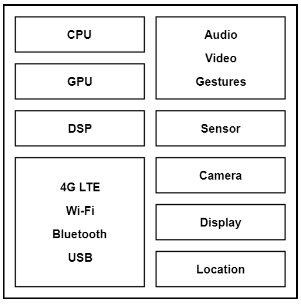


Fig. 1. The structure of an application processor

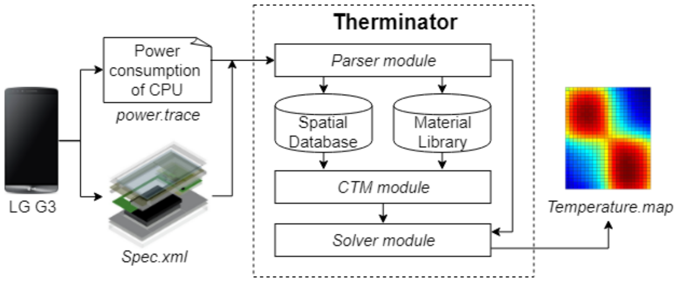


Fig. 2. The overview of Therminator architecture.

B. Thermal management model

The application processor has a thermal management model that controls the temperature of the smartphone. The thermal management model consists of a thermal engine, sensor drivers, and thermal management devices. Of these, the thermal engine is the main thermal monitor that runs during the operation of the device and it has two managers. One is a sensor manager that monitors the temperature from the on-die sensors located in high thermal density areas. The other is a device manager that controls the performance by setting the maximum CPU, GPU frequency and making it operate below that value, reduce the data throughput of the modem, restrict the maximum charge rate, reduce the display brightness, or various other methods. The thermal engine runs two thermal algorithms that are the threshold control algorithm and dynamic control algorithm. The threshold control algorithm performs thermal mitigation by limiting the frequency when it reaches a temperature threshold. The dynamic control algorithm adjusts the frequency according to the difference between a sensor measurement and a setpoint temperature. When the measured temperature is above the setpoint, it lowers the frequency and continues monitoring the temperature and adjusting the frequency until the measured temperature is reduced to below the setpoint.

III. Thermal simulator

The thermal management model of the application processor affects the temperature of the CPU. When the mobile device that is equipped in the application processor operates at high performance and the temperature increases, the temperature reaches a saturation point that does not exceed a certain temperature. This means that the thermal management model is operated and the performance decreases. Therefore, we use a thermal simulator to obtain steady-state temperature without reducing the performance.

Therminator that we used is the thermal simulator that calculates the steady-state temperature of the device [7]. It consists of three main modules: *parser*, *CTM*, and *Solver*, as shown in Fig. 2. A *Parser module* parses two input files, updates the material library, and makes the target device set of components. A *CTM module* makes the set of components into sub-components according to the resolution and stores them into the spatial database. In addition, it builds a compact thermal model for all sub-components. Finally, a *Solver module* computes the temperature of all sub-components using the compact thermal model and the power trace.

Therminator has two input files: *spec.xml* and *power.trace*. The *spec.xml* describes the design specification of the device as the component and contains information about the component such as its size, position, material, resolution, and whether power consumes. It contains information about the material such as its conductivity, specific heat, and density. The *power.trace* contains information about how much power is consumed at the component that is power consumes.

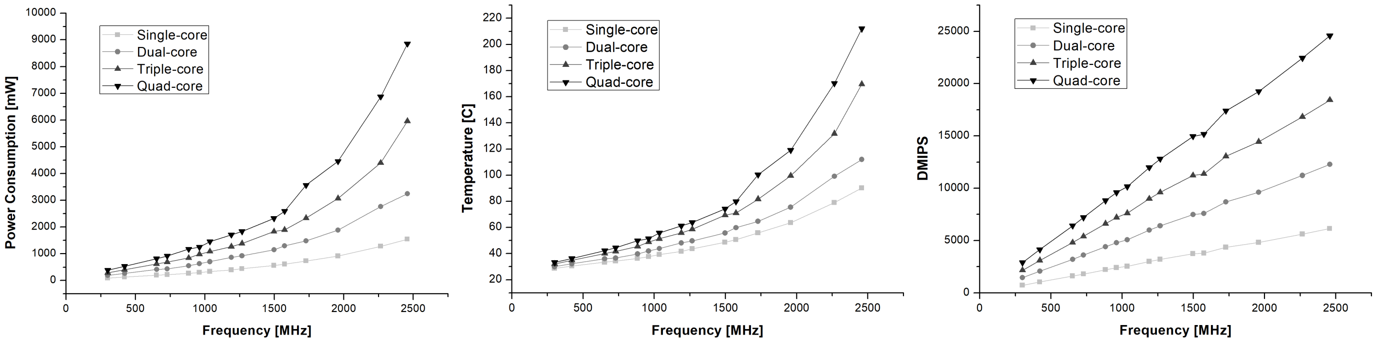
We proceeded as follows to make two input files for Therminator. To make *spec.xml*, we disassembled the target device [8] and measured the size and position of all components. For the built-in chip on the mainboard, we referred to the datasheet for modeling. Thus, we have completed a 3D model of the LG G3 that Snapdragon 801 modeled in detail to contain information about the four cores of the CPU and GPU. To make *power.trace*, we measured the power consumption of the CPU when operated at the same frequency in the multi-core. The method by which we measured power consumption is explained in the following section.

IV. Experimental environment

The target application processor is a Snapdragon 801 that is equipped in the LG G3. The Snapdragon 801 is a quad-core and consists of four Qualcomm Krait 400 CPUs with a clock speed of up to 2.5 GHz. The CPU operates at one of fifteen performance levels in the range 3002,500 MHz. The quad-core and fifteen performance levels have about 65,000 CPU operating patterns in theory. However, the CPU does not use all operating patterns and there is a sequence in which the core turns on and off. Therefore, we make the standard for the best performance that can be achieved with the frequency of each operating core. In other words, we set a total of 60 CPU operating patterns that all of them can operate at the same frequency in each multi-core.

A. Power consumption

The LG G3 test device was used to measure the power consumption of CPU. After fixing the number of operating cores and the operating frequency, we ran the *fast discharge* application that gives almost 100% of its workload to the CPU.



(a) CPU total power consumption (b) The average temperature of operating cores (c) CPU performance

Fig. 3. The experimental result as the number of operating cores and operating frequency.

Since the power consumption was almost constant, we used the average values consumed for a minute.

B. Steady-state temperature

With the two input files that were made, we used Terminator. We made *spec.xml* by 3D modeling the LG G3 and for *power.xml*, we used the measured values of the CPU power consumption. As CPU is the main cause of heating, to observe temperature solely as the change in CPU's power consumption, all power consumption was set to 0 except for the CPU.

C. CPU performance

We used Dhrystone to measure the CPU performance [9] and Dhrystone shows the CPU performance as an index of the DMIPS (Dhrystone Million Instructions per Second). However, since Dhrystone only supports a single thread, we measured the DMIPS of the single-core and used the DMIPS of the single-core in the multi-core. Since the Snapdragon 801 has the same four CPUs and we set the same operating frequency and maximum CPU load in a multi-core experiment, the DMIPS of the multi-core used the value multiplied by the DMIPS of the single-core and the number of operating cores.

V. Analysis of Power, Temperature, and Performance on the Multi-core

A. Characteristics of Power, Temperature, and Performance

We arranged the experimental results by power, temperature, and performance, respectively, against the number of operating cores and operating frequency, as shown in Fig. 3. The power, temperature, and performance generally increased as the number of operating cores and operating frequency increased. The power and temperature rose exponentially and in particular, it started to increase rapidly from about 1,500 MHz in the triple-core and quad-core. While the power increase for the single-core was small, that for the quad-core was large; therefore, it consumed considerable power at high frequency. The temperature was $> 90\,^{\circ}\mathrm{C}$ at a high frequency except for the single-core, and it rose up to $200\,^{\circ}\mathrm{C}$ in the quad-core. The performance rose linearly and had a value that averaged at 2.23 DMIPS/MHz.

B. Analysis of Power, Temperature, and Performance

1) Performance and Power: Fig. 4 shows that the performance improves as the power consumption increases. While performance improves rapidly at first, it shows a tendency to saturate afterward where the performance increases slowly. This means that the high-performance section is less effective as the power consumption increases. However, comparing different numbers of operating cores when using the same power, those operating with more cores perform better. In other words, increasing the number of cores when a device performs some operations means that it will consume less power.

2) Temperature and Performance: There is a relationship between temperature and performance as shown in Fig. 5. When the performance increases, the temperature increases exponentially. In other words, the rate of increase in temperature at the low-performance section is low, but the rate of increase in temperature at the high-performance section is high, so thermal should be considered when maintaining high performance. As can be seen in the graph, when operating at the same performance, the temperature decreases as the number of operating cores increases. Thus, the quad-core is the best operating core for both temperature and performance.

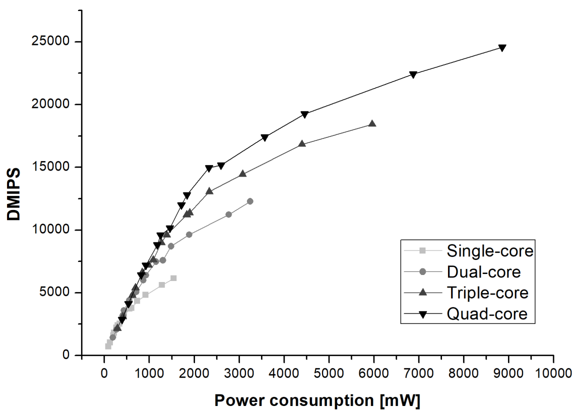


Fig. 4. The relationship between performance and power consumption

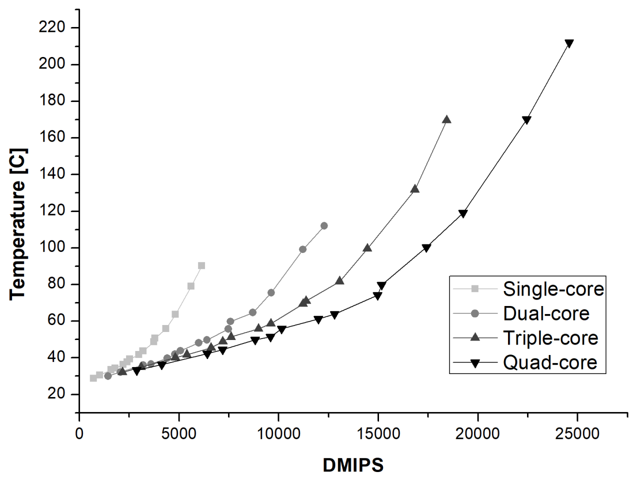


Fig. 5. The relationship between temperature and performance

C. Analysis at the same power and same performance

TABLE I shows the performance and temperature at the same power consumption for each operating core. Each power consumption, performance, and temperature (bold text) are the value for the single-core, dual-core, and triple-core (bold text) when they operate at their highest frequency. The values for each operating core below bold text are the performance and temperature values when it is operating at the same power consumption as the bold text operating core. As the number of operating cores increases, the performance improves and the temperature decreases. Thus, the quad-core has 75.54% better performance and 36.04% lower temperature than the single-core, 35.68% better performance and 16.42% lower temperature than the dual-core, and 15.22% better performance and 11.06% lower temperature than the triple-core.

Similarly, TABLE II shows the power consumption and temperature at the same performance for each operating core. The meaning of the bold text and others are the same as in TABLE I. Therefore, it can be seen that as the number of operating cores increases, the power consumption and temperature decrease for the same performance. Thus, the quad-core consumes 49.42% less power and has 53.94% lower temperature than the single-core, has 45.82% lower power consumption and 44.49% lower temperature than the dual-core, and consumes 31.89% less power and has 34.72% lower temperature than the triple-core.

TABLE I
THE PERFORMANCE AND TEMPERATURE AT THE SAME POWER CONSUMPTION.

	CPU		
	Power consumption [mW]	DMIPS	Temperature [°C]
Single-core	**1546.14**	**6142.29**	**90.13**
Dual-core		8847.68	66.40
Triple-core		10182.72	62.52
Quad-core		10781.96	57.65
Dual-core	**3247.16**	**12284.59**	**111.96**
Triple-core		14752.97	103.80
Quad-core		16667.94	93.58
Triple-core	**5958.74**	**18426.88**	**169.60**
Quad-core		21231.80	150.84

TABLE II
THE POWER CONSUMPTION AND TEMPERATURE AT THE SAME PERFORMANCE.

	CPU		
	Power consumption [mW]	DMIPS	Temperature [°C]
Single-core	**1546.14**	**6142.29**	**90.13**
Dual-core	887.09		48.76
Triple-core	783.30		44.01
Quad-core	781.97		41.51
Dual-core	**3247.16**	**12284.59**	**111.96**
Triple-core	2134.32		76.79
Quad-core	1759.15		62.15
Triple-core	**5958.74**	**18426.88**	**169.60**
Quad-core	4058.48		110.71

VI. CONCLUSION

In this paper, we studied the relationship between power consumption, performance, and temperature of the CPU based on the quad-core Snapdragon 801. We experimented by changing the number of operating cores and the operating frequency. We analyzed the power consumption, performance, and temperature of the CPU and confirmed the effective operating method for the CPU. Except for the performance when all cores were operating at a high frequency, we obtained the following results. For the same power consumption or the same performance, it is better to operate more cores in terms of the decreased power consumption and temperature and increased performance. Consequently, the quad-core has 75.54% better performance and 36.04% lower temperature than the single-core at the same power consumption. In addition, it has 49.42% and 53.94% lower power consumption and temperature at the same performance. Therefore, if the number of operating cores and operating frequency increases, the smartphone will have increased performance and can manage its power consumption and temperature more effectively since more cores available.

ACKNOWLEDGMENT

This research was supported by a grant (19PQWO-B153369-01) from Smart road lighting platform development and empirical study on test-bed Program funded by Ministry of the Interior and Safety of Korean government.

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