The Impact of Dust on On-chip Temperature And Performance of Microprocessors

Hyung Beom Jang[1], Cheol Hong Kim[2], and Sung Woo Chung[1]
Division of Computer and Communication Engineering[1],
Korea University, Seoul 136-713, Korea
{kuphy01, swchung}@korea.ac.kr
School of Electronics and Computer Engineering[2],
Chonnam National University, Kwangju 500-757, Korea
chkim22@chonnam.ac.kr

Abstract - *Temperature is a dominant factor in the performance, reliability, and leakage power consumption of modern microprocessors. With the advance of technology, thermal problems in microprocessor design get more crucial due to power density of microprocessors. As a result, more researchers have investigated thermal-aware techniques considering many factors such as ambient temperature [1]and characteristics of an application, which affect on-chip temperature of microprocessors. In fact, there is much possibility that dust in a heat sink deteriorates thermal problems of microprocessors. However, the impact of dust on on-chip temperature has never been studied. In this paper, we show that a heat sink covered with dust increases on-chip temperature, ultimately leading to performance degradation. Our evaluation results show that the performance of the same DTM (Dynamic Thermal Management) scheme is decreased, when we use a heat sink covered with dust (compared to that when we use a clean heat sink). Therefore, we recommend that computer users should clean their heat sinks for better performance.*

Keywords: Microprocessor, On-chip Temperature, Thermal Management, Performance Evaluation, Dust

1 Introduction

As process technology scales down, power density of microprocessors continuously increases leading to higher on-chip temperature. Excessively high on-chip temperature of microprocessors in turn threatens timing stability and lifetime reliability, resulting in physical damages in the worst case. In addition to reliability, temperature is tightly related to performance, leakage power, and cooling cost; i) performance can be gracefully sacrificed to alleviate thermal problems, ii) leakage power can be reduced by the decreased temperature, since leakage power is more than linearly proportional to temperature, and iii) cooling cost is increased to reduce temperature. In modern microprocessor design, temperature has become one of the most crucial considerations. In the past, thermal problems were resolved in the device or circuit level, which is not enough in the current technology. Thus, architectural thermal management techniques such as DTM (Dynamic Thermal Management) [6] were proposed. Naturally, there has been a significant increase of thermal-related publications in architectural conferences and journals.
On the other hand, there are some factors to affect on-chip temperature of microprocessors in addition to on-chip power dissipation. Ambient temperature affects on-chip temperature of microprocessor, since it varies across applications depending on convective heat flux from heat sources such as HDD, DRAM, and so on. Additionally, dust in a heat sink also increases on-chip temperature by preventing a heat sink from dissipating heat flux. However, as far as we know, there has not been any study on the impact of dust on on-chip temperature. Since on-chip temperature of microprocessors is

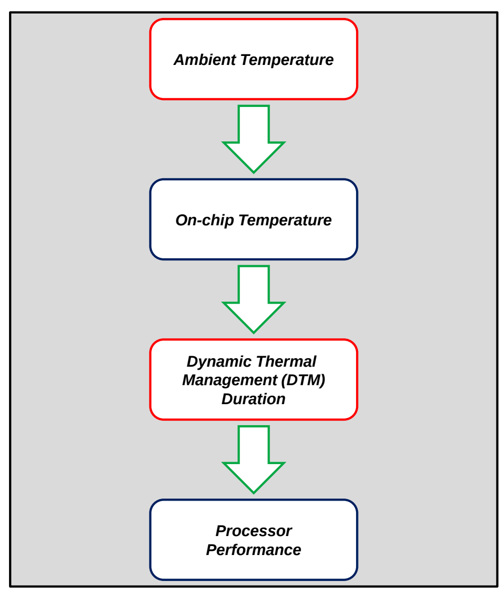

Fig. 1. The effect of ambient temperature on performance

[1] In this paper, ambient temperature denotes air temperature between processor and heat sink. Note that it is not room temperature.

highly affected by dust in the heat sink, considering the impact of dust on on-chip temperature is crucial. Note that it is easy to find dust on the heat sink of running processors. In this paper, we analyze the impact of dust on on-chip temperature and performance.

The rest of this paper is organized as follows. Section II explains previous work on architectural thermal management methods including architectural methodology to analyze the impact of ambient temperature. Section III describes experimental environments. Section IV analyzes the impact of dust on the heat sink on ambient temperature and performance. Section V concludes this paper.

2 Previous Work

For thermal management of processors, various techniques have been proposed. One of them is the DTM technique which dynamically controls power dissipation of processors referring to on-die temperature from CMOS thermal sensors, while trying to minimize performance degradation. In [1], thermal control techniques, such as DVFS (Dynamic Voltage Frequency Scaling) and decode throttling, were proposed for DTM. In DVFS, the clock frequency is dynamically scaled along with the supply voltage to reduce processor power, resulting in on-chip temperature reduction. On the other hand, in decode throttling, processor core is throttled by restricting the flow of instructions for reducing power consumption and on-chip temperature. However, in their efforts, they did not consider the impact of ambient temperature on on-chip temperature. Recognizing the importance of ambient temperature on on-chip temperature variation, researchers have tried to propose systematic thermal management schemes to reflect ambient temperature that does change depending on applications. Choi et al. incorporated ambient temperature analysis capabilities with their simulation methodology based on the CFD (Computational Fluid Dynamics) simulation [12]. In [3], Jang et al. found that different ambient temperatures should be used to evaluate a thermal management technique for different applications. They also evaluated the impact of application-dependent ambient temperature on the thermal evaluation results, such as performance and leakage power.

One can easily guess the effect of the dust in a heat sink on performance. Since dust in a heat sink deteriorates heat dissipation from a processor to outside, ambient temperature is increased; note ambient temperature represents air temperature between processor and heat spreader, not room temperature. The increased ambient temperature in turn leads to higher on-chip temperature, causing more frequent DTM invocations and eventually performance degradation, as shown in Fig. 1. Eventually, the dust degrades performance. Since computer users do not generally clean their computers, it is very probable that their heat sinks are covered with heavy dust. However, the effect of dust in a heat sink has never been quantitatively evaluated. In this paper, we analyze the impact of dust on on-chip temperature.

3 Experimental Environments

In this paper, we investigate the impact of dust on on-chip temperature by measuring ambient temperature that is not room temperature but air temperature between processor and heat spreader. If there is heavy dust in the heat sink, heat is not efficiently dissipated due to lowered heat dissipation capability of the heat sink. Naturally, ambient temperature between processor and heat spreader is increased. For measuring ambient temperature of the processor, we place off-chip thermal sensors (SEN-AP002P from Koolance Corporation [7]) as shown in Fig. 2 for two different heat sinks (a heat sink covered with dust and a clean heat sink). We use the computer system equipped with the 45nm Intel Core2Duo processor typically consuming 35 watts [9], 2GB Hynix DDR3 synchronous DRAM with the maximum TDP (Thermal Design Power) of 4.3 watts [11], a Hitachi 320GB SATA HDD with the activate-state TDP of 2.2 watts [8], an Intel GM45 north bridge chipset, a printed circuit board (PCB), a finned heat sink, an exhaust fan, and un-powered devices. The Intel GM45 north bridge I/O chipset of 12.0 watts [9] includes a graphic processing unit. For benchmark applications, we select ten applications from SPEC CPU2000 benchmark suite [10].

Additionally, to investigate the impact of dust on processor performance, we evaluate the DTM duration ratio [2] of the DTM schemes. We use the DVFS and stop-go (also known as global clock gating) schemes for DTM with the emergency temperature of 358K (85ºC) [9]. For the DVFS scheme, the Core2Duo processor supports three voltage/frequency pairs of 800, 1600, and 2533MHz that correspond to 0.95, 1.1, and 1.25V supply voltage, respectively. However, to consider the imprecision caused by on-chip thermal sensors; random noise and potential [6], we conservatively set the DTM invocation temperature to 355K (83ºC). In case of the stop-go scheme, when the temperature of the processor reaches 357K (84ºC)

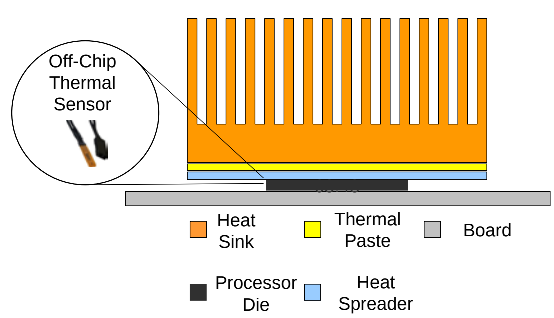

Fig. 2. Off-chip thermal sensor placement
to measure ambient temperature

[2] DTM duration ratio = (accumulated time when DTM is invoked) / (total execution time)

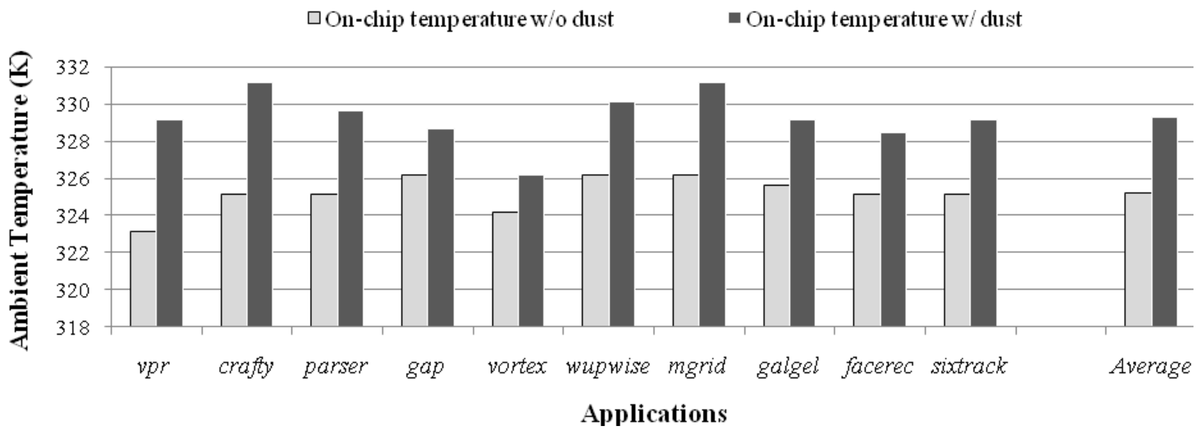

Fig. 3. Ambient temperature comparison.

[4], the processor is stalled for 10ms (doing nothing) by a thermal interrupt. When the temperature of the processor goes down below the threshold temperature, the processor resumes executions at the highest voltage/frequency pair.

4 Experimental Results

Fig. 3 shows ambient temperature for ten applications from SPEC CPU2000 benchmark suite, where ambient temperatures for two different heat sinks (a heat sink covered with dust and a clean heat sink) are depicted. The dust prevents a heat sink from dissipating heat flux from processors. Thus, heat flux from the processor is not be transferred to the cooling fan resulting in an increase of ambient temperature. With the heat sink covered with dust, ambient temperature of the processor is increased by up to 6 degrees, in case of *vpr* and *crafty*, since these applications consume large power over TDP with long execution time. In case of *vortex*, the ambient temperature is increased by 2 degrees showing the smallest ambient temperature increase due to the short execution time. When the execution time is short, the effect of dust is not so noticeable since heat is not propagated to the heat sink. The applications of ambient temperatures, which have very long execution time and large power consumption as much as the TDP, are increased over 3 degrees in *parser*, *mgrid*, *facerec*, and *sixtrack*. On average, ambient temperature of the processor is increased by 4 degrees due to the dust. The increased ambient temperature also leads to an on-chip temperature increase and the increased on-chip temperature of the processor in turn degrades performance. When the ambient temperature difference is 4.5, 1.1, and 2.6 degrees, on-chip temperature difference is 3.5, 0.7, and 2.0 degrees, on average, respectively for SPEC CPU2000 benchmark suite.

We estimate the performance differences of the processor with a dusty heat sink compared to that with a clean heat sink. Table 1 represents the DTM duration ratio and execution time for two DTM schemes (DVFS and stop-go) with different on-chip temperature, which are obtained from [3]; they ran all the applications from SPEC CPU2000 benchmark suite. When the difference of on-chip temperature ranges from 3 to 4 degree, the DTM duration ratio of the processor varies from 0% to 6.91% in both of DTM schemes, which is directly affected by on-chip temperature. The execution time of the DVFS scheme and stop-go scheme varies from 0.35% to 5.4% and from 0.67% to 9.77%, respectively. As ambient temperature difference is increased leading to on-chip temperature difference, the DTM duration ratio of the processor is increased, which it also increases execution time. In other words, the DTM technique frequently lowers the DVFS level to reduce the temperature of the processor below emergency

Table 1. The impact of on-chip temperature variation on performance of the processor

On-chip Temperature Difference	DTM Duration Ratio Variation		Execution Time Variation	
	DVFS Scheme	Stop-go Scheme	DVFS Scheme	Stop-go Scheme
0 ~ 1 degrees	0% ~ 0.08%	0% ~ 0.08%	0% ~ 9.88%	0.03% ~ 2.71%
1 ~ 2 degrees	0.11%~ 32.32%	0% ~ 2.66%	0.08%~ 3.96%	0.15% ~ 5.31%
2 ~ 3 degrees	0.24% ~ 0.28%	0.64% ~ 1.69%	0.24% ~ 0.5%	1.09% ~ 2.62%
3 ~ 4 degrees	0% ~ 6.91%	0% ~ 4.85%	0.35% ~ 5.4%	0.67% ~ 9.77%
Over 4 degrees	0.03% ~ 77.5%	0.02% ~ 25.74%	0.22% ~ 54.66%	0.02% ~ 73.88%

temperature, resulting in longer execution time. From evaluation results, we can know that the dust affects on-chip temperature variation and performance results which are not so small to be ignored.

5 Conclusion

In conventional thermal researches, on-chip temperature and performance have been evaluated without consideration of application/system dependent ambient temperature. Recently, there was a study to consider different ambient temperatures when evaluating different applications. However, there has not been any quantitative study to evaluate the impact of the dust in a heat sink on on-chip temperature, though the dust definitely deteriorates heat dissipation efficiency. In this paper, we found that the dust that has been ignored by computer users may deteriorate performance by up to 73.9%. Hence, we recommend that future computer users should remove the dust that is in their heat sinks for better performance.

Acknowledgement

This research was supported by the MKE(The Ministry of Knowledge Economy), Korea, under the ITRC(Information Technology Research Center) support program supervised by the NIPA(National IT Industry Promotion Agency) (NIPA-2011-C1090-1121-0010).

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